

University of Alberta

**Late Pleistocene – early Holocene plant macrofossils and pollen from the Yukon Flats,
central Alaska**

by

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A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of Master of Science

Department of Earth and Atmospheric Sciences

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I dedicate this thesis to my beautiful little niece, Hollie Joanne Robinson.

ABSTRACT

Dramatic climate changes and expansion of new biomes characterize the late Pleistocene – early Holocene of eastern Beringia. Analysis of plant macrofossils and pollen from three different sites in the Yukon Flats, central Alaska, record the past vegetation during the late Pleistocene -early Holocene (ca. 11,500 – 6,900 ^{14}C yrs BP) transition. The first paper deals with plant macrofossils associated with one of the earliest post glacial beaver dams (ca. 9,300 ^{14}C yrs BP) found in central Alaska. Vegetation reconstruction suggests a warmer than modern climate during the early Holocene. The second paper examines eight paleosols and their associated plant macrofossils and pollen within eolian deposits at two sites ranging from 11,500 – 6,900 ^{14}C yrs BP in the Yukon Flats. Spruce macrofossils were found in a paleosol dated at 10,700 ^{14}C yrs BP. High spruce pollen percentages (26%) were also recorded near the paleosol. This is the earliest post-LGM evidence for spruce in Alaska. Comparison with other post-glacial spruce records in Alaska, Yukon Territory and the Northwest Territories suggests a spruce refugium during the late Wisconsinian glaciation, perhaps in northwestern Canada.

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CHAPTER 1 – INTRODUCTION

1.1 Introduction

Since Hultén's (1937) study on the origin of modern flora of eastern Beringia, the paleoecological literature of Yukon and Alaska has two recurrent themes. Firstly, what is the composition of vegetation during the late Quaternary, in a region surrounded, but not directly affected, by glacial processes? That is, how much of the present day flora is a result of the re-expansion of refugial populations versus migration from areas south of the continental ice sheets? And secondly, what impact did abrupt climate oscillations, during the late Pleistocene – early Holocene (LPEH) interval, have on the Beringian landscape, specifically vegetation. Can vegetation reconstruction through this time provide inferences about the nature of the climate? This thesis sets to examine these questions by presenting a multi-proxy record of past plant remains, which are used to infer the local paleo-vegetation during the LPEH and responses to climate change.

The vegetation of Alaska during the LPEH has primarily been reconstructed from pollen analyses of lacustrine deposits. Central Alaska pollen records generally agree that at 14,000 cal. yrs BP, an expansion of birch occurred replacing sparse herb tundra, followed by poplar (11,500 – 9,500 cal. yrs BP) and later by the presence of spruce and alder by 9,500 cal. yrs BP (Figure 1.1). At 9,000 cal. yrs BP the regional vegetation was probably birch-spruce woodland, with alder trees in more mesic sites. By 6,500 cal. yrs BP, black spruce was common where acidic, peaty conditions prevailed (Edwards et al., 2001). Pollen analysis has been the preferred method to reconstruct late Quaternary paleoecological records because pollen grains are abundant and studies can be compared with relative ease. However, pollen analyses from lacustrine sediments cannot distinguish between local and regional vegetation. Moreover, datable organic material from arctic lake sediments are often used for establishing chronologies in pollen records, are subject to old

carbon contamination, which may offset the C^{14} age by centuries or more (Abbott and Stafford, 1996; Abbott et al., 2000). Plant macrofossils from terrestrial settings can aid pollen analyses. Plant macrofossils are considered local components of vegetation and due to unique morphological characteristics, they can often be identified to a lower taxonomic level (i.e. species level). As well, most terrestrial plant macrofossils can be directly Accelerator Mass Spectrometry (AMS) dated, eliminating the possibility of old carbon contamination (Birks and Birks, 2000).

The vegetation of eastern Beringia has been subject to previous climate changes in the Quaternary. The impact of climate change on the adaptation of species is important for future flora and faunal survival (i.e. what affect does future global warming have on the spread of boreal and shrub elements? Are these species capable of tracking anthropogenic warming?). In particular, the question of whether spruce populations survived in the northern or southern refugium has important implications for the migration, diversity and adaptation of boreal forests in the future. The history of late Quaternary spruce (*Picea* spp.) in northwestern North America is a subject of debate among paleoecologists. Two leading hypotheses have been advanced to explain how spruce migrated into modern Alaska and the Yukon. The first hypothesis suggests that spruce survived in a refugia south of the Laurentide Ice Sheet, in the continental United States. Spruce then migrated northwards into eastern Beringia, following recession of continental ice sheets (Figure 1.2 A). The "southern refugia" hypothesis is based on low spruce pollen percentages and a lack of spruce macrofossils in eastern Beringia, in deposits dated to the Last Glacial Maximum (Hopkins et al., 1981; Ritchie and MacDonald, 1986). The second hypothesis suggests that spruce and other boreal elements survived the Last Glacial Maximum in sparse and scattered populations in eastern Beringia, which expanded following deglaciation and the amelioration of climate (Figure 1.2 B). The "northern refugia" model is based on a re-examination of low spruce pollen percentages, supposed unrealistic south to north migration rates

(Brubaker et al., 2005), and genetic evidence from extant spruce populations in Alaska (Anderson et al., 2006).

Plant macrofossils and pollen grains are excellent proxies for past climate changes. They are generally well-preserved and abundant on the landscape, offering an opportunity to reconstruct the local vegetation and its response. Remains of terrestrial vegetation also have the advantage of recording abrupt climate changes almost simultaneously. As well as the difficulties with carbon contamination, lake pollen deposition is subject to changes in lake processes, and may not be a clear continuous record of what is happening on the landscape. As an alternative, in Alaska, and in particular the Yukon Flats region of central Alaska, there are a number of loess-paleosol sequences (Muhs et al., 2003) (Figure 1.3). Post glacial loess of the Yukon Flats is exposed by lateral migration of the modern Yukon River (Williams, 1962). Potentially, these loess exposures may provide continuous proxy records detailing the vegetation of the local landscape and any impact of abrupt climate change (Begét, 2001). Specifically, these loess-paleosol sequences may contain identifiable plant macrofossils and pollen, which would provide crucial paleoenvironmental records in an area understudied.

The LPEH transition is marked by a series of abrupt millennial-to-century scale warm/cold oscillations including the Allerød interval (13,350 – 12,650 cal. yrs BP), an abrupt warming near the end of Marine Isotope Stage 2 (Peteet, 2000), and the Younger Dryas chronozone (12,650 – 11,550 cal. yrs BP), an abrupt cold event lasting roughly one thousand years (Figure 1.1) (Litt et al., 2001). Evidence of these oscillations is recorded in the North Atlantic Ocean and Greenland ice cores (Figure 1.1) (Alley et al., 1997; Bond et al., 1997) and in the adjacent borderlands (Björk et al., 1996). In northwestern North America however, evidence for the Allerød interval is sparse (Peteet, 2000; Hu et al., 2006). The most provocative record suggesting considerable climate impact comes from the large mammal records of Guthrie (2006). He reports new

radiocarbon dates on vertebrate remains from Alaska and the Yukon, which indicate that ecological replacement and subsequent displacement, from post glacial climate oscillations, caused a faunal turnover from large mammals, including mammoth and horse, to smaller mammals (Figure 1.1) (Guthrie, 2006). The only other record attributed to the Allerød shift is an increase in spruce pollen in Siberian lakes around that time (Bezrukova et al., 2005). The evidence thus far is inconclusive as to whether North Pacific regions were affected by this abrupt warming period. Impacts of the Younger Dryas in northwestern North America are better documented though still small in number compared to North Atlantic regions. Such evidence of the Younger Dryas in eastern Beringia includes a reverse from shrub to herb vegetation and glacial re-advancements in alpine regions (Elias, 2000; Briner et al., 2002; Hu et al., 2002; Axford and Kaufman, 2004). Evidence of abrupt climate changes in North Pacific regions, which are near synchronous with records in the North Atlantic regions may suggest that the scale of such events are more extensive than previously thought (Peteet, 2000).

Following the Younger Dryas was the relatively stable early Holocene, where dramatic landscape changes occurred, including the expansion of boreal elements. Evidence of an early Holocene thermal maximum in Alaska, Yukon and other arctic areas suggests that summer temperatures were warmer than modern (Kaufman et al., 2004). Documenting the spatial scale of the Allerød, Younger Dryas and early Holocene requires more vegetation records beyond the North Atlantic borderlands, ideally from terrestrial settings.

This thesis presents two papers dealing with the late Pleistocene – early Holocene transition in central Alaska. The first paper presents an early Holocene vegetation record (ca. 9,300 ^{14}C yrs BP) from central Alaska based on plant and bryophyte macrofossils associated with a beaver dam deposit. The purpose of this paper is to record a snapshot of the biogeography of a local area during the early Holocene, a time of climate amelioration following the last glaciation. The

second paper reports a near-continuous terrestrial record of plant macrofossil and pollen remains that cover the LPEH transition, along the Yukon River in the Yukon Flats, central Alaska. The purpose of this study is to record the paleo-vegetation and its responses during a time of abrupt climate change. The multi-proxy nature of this thesis allows inferences on a number of important topics in eastern Beringia paleoecology.

I performed the fieldwork, plant macrofossil analyses and stratigraphy, and wrote the two papers included in this thesis. Dr. Duane Froese's contributions included general advice on the subject matter, funding, editing of the thesis and fieldwork. Dr Alwynne Beaudoin assisted with plant macrofossil analysis and editing of the thesis. Dr. Charles Schweger performed the pollen analysis and helped with the editing. Jennifer Doubt examined the bryophyte data and helped edit the first paper of the thesis. The first paper has been submitted and accepted for publication in the journal, *Arctic*, and the second paper is intended to be submitted to the journal, *Quaternary Science Reviews*.

5

Biozones	Vegetation	Paleoclimate	Fauna			
Holocene	Black Spruce	Warm and Moist				
	6,500 Alder	Warm and Moist				
	8,500 White Spruce	Warm and Moist				
	9,500 Poplar	Warm and Dry				
11,550 Younger Dryas	Birch	Cool and Dry	Mammoth	Bison	Wapiti	Moose
12,650 Allered						
13,350 Older Dryas						
13,540 Belling						
13,790 Oldest Dryas						
13,925 Melandorf						
14,000	Herb	Cold and very dry	Horse			
14,575						

Figure 1.1: Average biozone ages (in cal. yrs BP) of North Atlantic climate oscillations during the late Pleistocene – early Holocene from Litt et al. (2001). Colours represent warm or cold climate intervals, respectively. Vegetation zones (in cal. yrs BP) and interpreted paleoclimates are generally accepted for central Alaska from Edwards et al. (2001). Faunal presence in Alaska and the Yukon are provided by radiocarbon ages from Guthrie (2006).

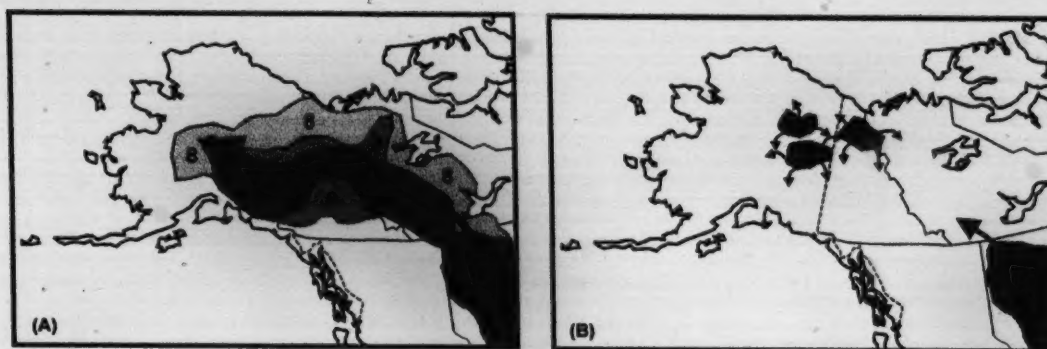


Figure 1.2: (A) The “southern refugia” hypothesis proposes spruce migrated from southern areas, re-populating eastern Beringia (Alaska and the Yukon Territory) following the recession of large ice masses and amelioration of climate. (B) The “northern refugia” hypothesis proposes that spruce survived in eastern Beringia during the last glaciation and re-populated the region simultaneously with migration from the south.

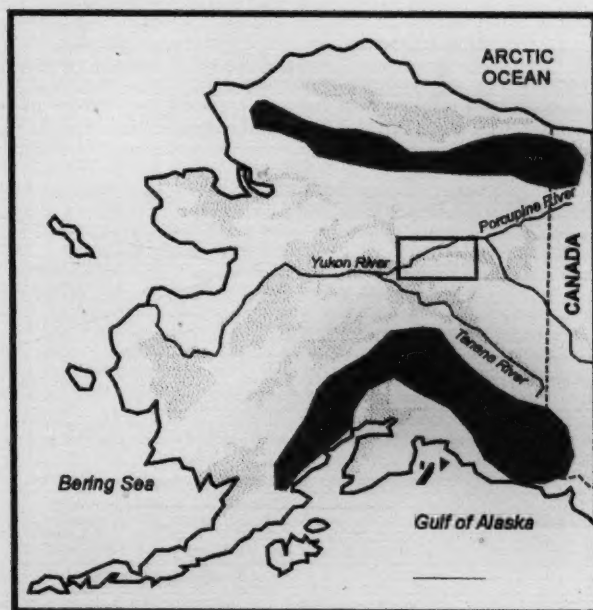


Figure 1.3: Late Quaternary loess deposits in Alaska from Muhs et al. (2003). Location of study area highlighted by box.

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CHAPTER 2 - PLANT MACROFOSSILS ASSOCIATED WITH AN EARLY HOLOCENE BEAVER DAM IN INTERIOR ALASKA

2.1 Introduction

Dynamic changes in the east Beringian landscape and its biota during the late Pleistocene – early Holocene transition were characterized by increased solar insolation (Bartlein et al., 1992; Kaufman et al., 2004), the expansion of new biomes (Bigelow and Powers, 2001; Brubaker et al., 2005; Edwards et al., 2005), the extinction of large mammals (Guthrie, 2006), and the arrival of humans (Yesner, 2001). Vegetation of this time has been reconstructed primarily through pollen analysis of lacustrine sediments (Ager, 1975, 1983; Anderson and Brubaker, 1994; Edwards and Barker, 1994; Bigelow and Edwards, 2001). Pollen, however, has disadvantages as a proxy for vegetation, including limitations in taxonomic resolution, regional and local integration of pollen, and low pollen productivity and input in treeless environments (Birks, 1980; Birks and Birks, 2000). In contrast, plant macrofossils are more representative of the local vegetation than pollen and can commonly be identified to species level. Moreover, individual macrofossils can be radiocarbon dated by accelerator mass spectrometry (AMS), confirming the local presence of a particular taxon at a specific time. Previous studies in Beringia that have included plant macrofossil analyses have yielded valuable records of local vegetation (e.g., Carlson and Finney, 2004; Edwards et al., 2005).

Plant macrofossils can be recovered from a variety of materials and sedimentary contexts. However, plant macrofossils, unlike pollen, are not abundant and are not widely dispersed; therefore, sediments from large lakes generally yield few macrofossils. Small ponds are more likely to yield a suite of plant macroremains that are representative of the local vegetation. In boreal areas, beaver ponds provide such a depositional setting. The ponds are created when modern beaver (*Castor canadensis* L.) dam small streams using wood from surrounding

vegetation, which they also store at the bottom of the pond for future food supply. Beaver ponds gradually infill with sediment containing plant macrofossils and wood from the dam that can be radiocarbon dated (Rains, 1987). Here we report a macrofossil record from an early Holocene beaver pond in central Alaska, which provides insight into the early post-glacial vegetation of the area.

2.2 Study location and setting

The beaver pond is seen as an organic collection of beaver-chewed wood and sandy silt near the top of a ca. 50 metre high bluff of loess on the east bank of the Yukon River, approximately two kilometers downstream from the Dalton Highway bridge in central Alaska (Figure 2.1). Most of the Yukon River in this part of Alaska is braided but at this site the river flows in a single channel within a relatively narrow floodplain confined by bedrock slopes. Discontinuous permafrost occurs throughout the area and modern ice wedges are exposed by landslides near the bluff (Froese et al., 2005).

The climate of the region is subarctic and continental. Temperatures at Fort Yukon, approximately 170 km east of the site, range from 30°C in the summer to -60°C in the winter. The July mean temperature is about 15°C and the annual mean is -4°C, resulting in discontinuous permafrost in the area. Annual precipitation is 170 mm at Fort Yukon (NCDC 1949 – 2000 for Fort Yukon, Western Regional Climate Centre).

Boreal forest of white spruce (*Picea glauca*) and black spruce (*Picea mariana*), grows on uplands and the floodplain of the Yukon River (Viereck et al., 1992). Low willow (*Salix planifolia*), thinleaf alder (*Alnus tenuifolia*) and sedges (*Carex* spp.) are also present on the floodplain. Forbs, especially sage (*Artemisia frigida*) and grasses, including *Festuca altaica*, occur on south-facing

bluffs in interior Alaska. Upland spruce forest includes stands of balsam poplar (*Populus balsamifera*) and paper birch (*Betula neoalaskana*). Willow (*Salix* spp.), alder (*Alnus*), and quaking aspen (*Populus tremuloides*) grow on well drained soils in these uplands (Viereck et al., 1992, 1993). *Sphagnum* spp. are common in lowland wet areas. Common mosses on forest floors are *Hylocomium splendens*, *Rhytidium rugosum*, *Pleurozium schreberi* (Viereck et al., 1992).

2.3 Methods

Fieldwork was conducted in August 2002 and June 2005. The section was photographed, including the beaver-chewed wood near the top of the bluff. Samples were collected and a stratigraphic description was prepared (Figure 2.2). Each sample consisted of about 500 ml of sediment, collected using a trowel from a cleaned exposed section. Samples were placed in sealed plastic bags to prevent contamination and sample degradation. Plant macrofossil results are reported for the 2005 samples, though some moss taxa are reported from the 2002 samples.

Samples were analyzed in the Paleoenvironmental Laboratory at the Royal Alberta Museum. Vascular plant macrofossils were identified by S.C. Robinson and A.B. Beaudoin; bryophytes were identified by J. Doubt. Fifty millilitre samples were measured by water displacement for consistency and comparisons. They were sieved on a 90 μ m mesh screen to remove finer sediment. Material coarser than 90 μ m was screened through 2 mm, 1.18 mm, 500 μ m, 250 μ m and 90 μ m meshes and sorted into mosses, roots, bark, leaf fragments, wood, bones, and seeds using a binocular dissecting microscope at 12 x magnification. In this paper, the term "seeds" is used in a broad sense and includes achenes, nutlets and samaras. Abundance of each group and the general condition of the plant macrofossils were noted. Abundance was estimated from coverage on a Petri dish and rated from one to five, with one being a trace and five being abundant. Seeds and bryophytes were identified to the lowest taxonomic level possible, with the

aid of literature (Nyholm, 1954; Berggren, 1969; Lawton, 1971; Montgomery, 1977; Steere, 1978; Porsild and Cody, 1980; Crum and Anderson, 1981; Levesque et al., 1988; Warner, 1990; Clifford, 1991; Smith, 1993; Cody, 1996; Hurd et al., 1998) and reference collections in the Paleoenvironmental Laboratory and the Herbarium at the Royal Alberta Museum. Wood was identified by R.J. Mott.

2.4 Results

Stratigraphy

The beaver dam is two to three metres below the top of the bluff, approximately 50 metres above river level (Figure 2.2). The presence of the dam is not indicative of changes to the Yukon River, but rather was likely a result of damming of a small stream on the upland landscape, probably fed by thaw lakes and ponds. The dam itself is about one metre thick and contains abundant, densely packed beaver-chewed wood fragments (Figure 2.3) lying flat within a sandy silt matrix. It is underlain by one metre of sandy silt, which contains gastropods, some twigs, and discontinuous fibrous organic beds, overlying massive inorganic sandy-silt (loess) of much greater age. Overlying the beaver dam is one metre of crudely stratified sandy silt containing some wood. The sandy silt is overlain by a 0.3 metre thick bryophyte-rich organic layer, which in turn is overlain by sandy silt, to the top of the bluff. The latter sandy-silt is interpreted as primary loess which accumulated following drainage of the pond.

Radiocarbon ages

Three samples of beaver-chewed wood from the lower, middle and upper parts of the beaver dam were radiocarbon dated (Table 2.1 and Figure 2.2). The lower sample (*Populus* sp.) yielded an age of 9280 ± 90 yrs BP (GSC-6701); the middle sample (*Populus* sp.) returned an age of 9290 ± 90 yrs BP (GSC-6703); and the upper sample (*Salix* sp.) yielded an age of 9280 ± 90 yrs BP (GSC-6705). Calibration of these conventional ages using Oxcal v 3.10 (Bronk Ramsey 2005) gives an age range of 10580 – 10290 cal. yrs BP (2 sigma). Comparison with other dated sites in eastern Beringia (Table 2.1) indicates that the beaver dam at the Dalton Highway bridge site is one of the earliest Holocene occurrences of beaver in the region.

Plant Macrofossils

The plant macrofossil assemblage (Table 2.2 and Figure 2.2) represents 16 emergent and aquatic forbs, four graminoids, five shrubs, and 19 mosses. No arboreal taxa are recorded in the assemblage, other than the wood in the beaver dam itself. This includes willow (*Salix*) and poplar (*Populus*) wood, which must have been growing adjacent to the site.

Seeds

Abundances of seeds vary vertically through the beaver dam and bounding sediments. Samples SR05-DH1 and SR05-DH2 contain only one achene from *Ranunculus* sp. and *Typha latifolia* seeds. Macrofossil abundance is much greater within the beaver dam. SR05-DH3, the lowest of the beaver dam samples, contains remains of shrubs, forbs and graminoids. Shrubs are dominated by *Betula* sp. and *Betula glandulosa*; *Arctostaphylos uva-ursi* and *Rubus* sp. are also present. Cyperaceae include *Carex* spp. and *Eleocharis palustris*. *Typha latifolia* is common and *Potamogeton* sp. is present. Sample SR05-DH4, from the middle of the dam, contains emergent and aquatic macrofossils including *Typha latifolia*, *Potamogeton* cf. *foliosus*, *Potamogeton*

pusillus and *Polygonum lapathifolium*. The upper beaver dam sample, SR05-DH5, contains the most abundant *Typha latifolia* achenes in the sequence and increased numbers of *Chenopodium* sp. (type 1) seeds. It includes remains of several shrubs, graminoids and forbs, including first occurrences of *Najas flexilis*, *Hippuris vulgaris* and *Shepherdia canadensis*. Sample SR05-DH6, from the sandy silt overlying the beaver dam, records a substantial decrease in the number of seeds, especially of *Typha latifolia*, *Chenopodium* sp., *Betula* sp and *Betula glandulosa*. The highest sample, SR05-DH7, which is from the bryophyte layer, contains no shrub macrofossils, and forbs are represented by only three *Potentilla palustris/rubricaulis* seeds. The major wetland species are absent, but *Carex* sp. seeds are abundant.

Mosses

Emergent wetland species associated with shallow, stagnant or slow-moving water, including *Warnstorfia* spp. and *Drepanocladus aduncus*, dominate the moss fraction of macrofossils in all samples collected in 2005 (Table 2.3). Species associated with moist and dry terrestrial sites are less frequent, and only in some samples. In contrast, upland species dominated some 2002 samples. The apparent discrepancy between 2002 and 2005 samples probably reflects the local response of moss species to microhabitat variability or the local incorporation of upland moss species as beaver dam caulk.

Samples SR05-DH1 and SR05-DH2, from below the beaver dam, contain few moss fragments and those are *Warnstorfia* sp. (Table 2.3 and Table 2.4). Samples SR05-DH3 and SR05-DH4 (the lower and middle beaver dam samples) have 11 and 10 species of mosses, respectively, and include non-aquatic species such as *Amblystegium serpens*, *Ceratodon purpureus*, *Dicranum undulatum*, *Hylocomium splendens*, *Leptobryum pyriforme*, and *Rhytidium rugosum*.

Hylocomium splendens and *R. rugosum* dominate the 2002 sample from this level. Most moss

species from samples SR05-DH5 and SR05-DH6 are emergent wetland taxa, such as *Calliergon* spp., *Drepanocladus aduncus*, and *Warnstorfia* spp. (Table 2.3). The number of species is lower in those samples than in samples SR05-DH3 and SR05-DH4. Moss macrofossils are most abundant in sample SR05-DH7, although only five species, all wetland emergents, are represented (Table 2.3). *Scorpidium scorpioides*, which is found in nutrient-rich pools and shores (Crum and Anderson 1981), dominates the moss assemblage at this level.

Abundance

The abundance chart (Table 2.4) shows that macrofossil groups differ through time. The most notable differences are between the three beaver dam samples (SR05-DH3, SR05-DH4 and SR05-DH5) and the samples underlying (SR05-DH1 and SR05-DH2) and overlying (SR05-DH6 and SR05-DH7). The underlying samples contain small amounts of wood, bark, stem and mosses. Nearly all groups are present in the three beaver dam samples with bark and wood being most abundant. The overlying samples show a reduction of most groups with the exception of stem parts and mosses, which are both abundant.

2.5 Discussion

Early Holocene vegetation in interior Alaska

The plant macrofossil data (Figures 2.2 and 2.4) provide a detailed record of the local vegetation and the evolution of a beaver dam and pond in interior Alaska, for a brief interval in the early Holocene. Based on modern analogues, samples SR05-DH1 – SR05-DH6 record a pond with emergent forbs growing at its edges. Sedges and shrub birch were present near the pond. SR05-DH7 records the establishment of a sedge community on the drained or infilled pond indicating a

typical terrestrialsation sequence (Beaudoin et al., 1996). The dominance of aquatic/emergent mosses in sample SR05-DH7 indicates that despite the declining moisture suggested by the vascular plant remains, standing water persisted at this time.

The bryophyte macrofossils reveal aspects of local vegetation additional to those revealed by the vascular plant macrofossils. Bryophyte richness correlates with boreal microhabitat diversity (e.g., Vitt et al., 1995; Crites and Dale, 1998; Vitt et al., 2003; Gignac and Dale, 2005). Thus, the small number of species in the lowermost and uppermost samples suggests that the site was homogeneous and wet, with little topographic relief. The ecological preferences of moss species in samples SR05-DH1 and SR05-DH2 support conclusions, drawn from vascular plant remains, that the site was influenced by still or slow-moving water. Mid-sequence samples (SR05-DH3 and SR05-DH4) have more diverse moss assemblages, suggesting an increase in moss microhabitats. Several possible explanations for the occurrence of upland species in these samples exist. For example, the local microhabitat heterogeneity of the dam itself may have supported a greater number of species. Alternatively, the dam may have acted as a sieve for water draining through it, trapping fragments of upland species that were transported by flood water or other means from the pond banks, or upland species may have been introduced as caulk material by beavers.

Although the plant macrofossil and bryophyte data are in general agreement, there is an inconsistency. The emergent basiphile *Scorpidium scorpioides* is abundant in the uppermost sample (SR05-DH7) suggesting nutrient enrichment and water saturation. In contrast, vascular plant macrofossils in this sample, particularly *Carex* sp., are suggestive of acidic and increasingly dry soil conditions.

It is surprising that *Populus* seeds or catkin bracts were not found in the assemblage because poplar wood is present in the beaver dam and poplar pollen is a component of other interior records (Ager, 1975, 1982; Cwynar, 1982; Edwards et al., 1985; Anderson et al., 1988, 1990; Hu et al., 1993; Brubaker et al., 2001). The absence of poplar seeds despite the presence of poplar wood, however, has been noted elsewhere (e.g., Beaudoin et al., 1996).

The spread of spruce (*Picea*) after the Last Glacial Maximum is a topic of interest in Beringian studies. Samples from the Dalton Highway bridge site do not contain spruce macrofossils, suggesting that it was not present in the vicinity ca. 9300 ^{14}C yrs BP, though spruce wood is not generally sought after by beaver. Based on pollen records, spruce seems to have appeared on a regional scale in central Alaska 9000 – 8500 ^{14}C yrs BP (Brubaker et al., 1983; Anderson et al., 1990; Edwards and Barker, 1994) although Hu et al. (1993) and Ager and Brubaker (1985) suggest a slightly earlier appearance at ca. 9500 ^{14}C yrs BP.

The presence of cattail (*Typha latifolia*) and nodding water-nymph (*Najas flexilis*) in our record could have implications for early Holocene climate. The modern northern limit of cattail, is near our site, at Mayo in central Yukon and Fairbanks in central Alaska (Figure 2.1) (Porsild and Cody, 1980). Edwards and McDowell (1991) confirm that *Typha latifolia* is near its northern limit in the Fairbanks area. *Najas flexilis* in Alaska is less understood, but has a similar modern distribution to that of *Typha latifolia*. The *Typha latifolia* and *Najas flexilis* seeds at our site are well preserved and are unlikely to have been transported to the site from more southerly locations. This finding indicates that both species were at the northern most range of their distributions in the early Holocene, and suggest that the climate could have been warmer compared to today, consistent with other studies in the region (eg. Kaufman et al., 2004).

The implications of the presence of early Holocene beaver in central Alaska

The beaver dam has important local implications for landscape and climate conditions during the early Holocene. This site yields evidence for one of the earliest occurrences of beaver in Alaska following the last glaciation (Table 2.1). No beaver remains dating to the last glaciation have yet been found in Alaska. The absence of beaver at this time may be due to a lack of trees in the region or a cold and arid climate unsuitable for beaver habitation. Evidence for late Pleistocene beaver prior to the last glaciation is limited to a single non-finite radiocarbon age of $>38\,600\text{ }^{14}\text{C}$ yrs B.P which may be associated with the mid-Wisconsinan interstadial (MIS 3), but evidence for beaver during this interval is not overwhelming (Harington, 2003). Earlier evidence for beaver, in the form of beaver chewed wood associated with the last interglacial forest bed in central Alaska, which may be attributable to modern beaver (*Castor* sp.) or perhaps giant beaver (*Castoroides*) remains unclear (Matheus et al., 2003). Fossils of giant beaver are known from the Old Crow region, northern Yukon and may be of last interglacial age where they may have coexisted with modern beaver (Harington, 1978). The size of the tooth marks on the chewed wood will normally distinguish between the modern or giant beaver. The beaver dam at our site contains wood that is cut by the modern beaver. The composition of the dam at the Dalton Highway bridge site is mainly that of willow and poplar/aspen wood, which is the preferred diet of beavers (Hakala, 1952; Murray, 1961), indicating that the climate had become warmer prior to dam construction. The trees from which the dam was built are unlikely to have been transported to the site by a stream, rather they were cut from local sources by beavers.

The beaver dam and plant macrofossil data at our site record local vegetation and landscape changes during the last glacial-interglacial transition. We suggest that the interconnecting thaw ponds are indirectly linked to the regional changes in temperature and moisture availability, and the thaw unconformity recorded in interior Yukon and elsewhere during the early Holocene (Burn

et al., 1986; Abbott et al., 2000; Mann et al., 2002). The presence of *Typha latifolia* and *Najas flexilis* at their northern limits is important in interpreting a warmer than present early Holocene environment.

2.6 Conclusions

Plant macrofossils provide detailed records of local vegetation of a beaver-dammed pond in the early Holocene of central Alaska. The beaver dam provides evidence for one of the earliest occurrences of *Castor canadensis* in Alaska at ca. 9300 ^{14}C yrs B.P. The presence of seeds of *Typha latifolia* and *Najas flexilis* at their modern limits and the beaver dam itself suggest slightly warmer temperatures and availability of flowing water in the early Holocene than today.

Table 2.1: Radiocarbon ages of beaver fossils and beaver-chewed wood in Alaska, Yukon and N.W.T.

Location	Dated material	Age (^{14}C yrs BP)	Reference
West of Mackenzie River, N.W.T.	Beaver-gnawed wood	>38 600 (GSC-120)	R.E. Morlan, CMC database (1999)
Hungary Creek, Bonnet Plume Basin, Yukon.	Beaver-gnawed wood (<i>Picea</i> sp. or <i>Salix</i> sp.)	36 900±300 (GSC-2422)	Hughes et al. (1981)
5 km SE of Sabine Point, Yukon	Beaver-gnawed wood (<i>Populus</i>)	9940±90 (GSC-2022)	Lowdon and Blake (1979)
Dome Creek, Fairbanks, Alaska	Sticks in beaver dam, not chewed (<i>Populus</i> , <i>Salix</i>)	9650±140 (Beta 69,379)	Péwé et al. (1997)
Near Arctic Red River, N.W.T.	Beaver-cut sticks from organic sediments	9500±90 (GSC-1814)	Lowdon and Blake (1979); Harington (1978)
Fairbanks Creek, Fairbanks, Alaska	Beaver-chewed wood (a) <i>Populus</i> , (b) <i>Salix</i>	(a) 9350±80 (Beta 58,408) (b) 13 600±600 (1952 solid carbon date L1171)	Péwé et al. (1997)
Washington Creek, Alaska	Beaver-cut wood from dam	9330±300 (W-2160)	Harington (1978)
Dalton Highway bridge, Alaska	Beaver-chewed wood (<i>Populus</i> , <i>Salix</i>)	9280±90 (GSC-6705) 9290±90 (GSC-6703) 9280±90 (GSC-6701)	This paper This paper This paper
Upper Eva Creek, Fairbanks, Alaska	Beaver-chewed sticks in beaver dam (<i>Picea</i>)	8940±80 (Beta 46,215)	Péwé et al. (1997)
Dome Creek, Fairbanks, Alaska	Beaver-chewed log (<i>Populus</i>)	8800±70 (Beta 50,685)	Péwé et al. (1997)
Upper Eva Creek, Fairbanks, Alaska	Beaver-chewed sticks in beaver dam (<i>Salix</i>)	8780±100 (Beta 48,788)	Péwé et al. (1997)
Mouth of Old Wound, Alaska	Log from beaver dam (<i>Betula</i> or <i>Populus</i>)	8480±300 (W-2596)	Hopkins et al. (1981)
Mud Creek, near Candle, Alaska	Beaver-chewed wood (<i>Betula</i>)	8080±300 (W-2808)	Hopkins et al. (1981)
Dawson Cut, Fairbanks, Alaska	Log of a beaver dam (<i>Picea</i>)	7280±80 (Beta 50,683)	Péwé et al. (1997)
Acasta Lake, N.W.T.	Fossil remains of beaver	7000 (suggested from charcoal)	Harington (1978)
Sullivan Creek, Hot Springs District, Alaska	Beaver-chewed log (<i>Betula</i> or <i>Populus</i>)	6820±200 (W-733)	Hopkins et al. (1981)
Sullivan Pitt (Tofty Placer District), Alaska	Logs extracted from a mass of beaver-gnawed wood	6730±260 (W-1108)	Harington (1978)
Sheep Creek, Fairbanks, Alaska	Beaver-chewed wood (<i>Populus</i>)	6100±80 (Beta 52,700)	Péwé et al. (1997)

Notes: Evidence of beaver remains or chewed-wood adapted from Harington (2003)

Table 2.2: Plant macrofossils from Dalton Highway bridge site

Taxa	Common name	Macrofossil type	Numbers	%	Habitat description
Trees and Shrubs:					
<i>Betula</i> sp.	Birch	Samaras	33	6.20	Acidic rocks, woodland
<i>Betula glandulosa</i>	Dwarf birch	Samaras	32	6.01	muskegs, peat bogs
<i>Shepherdia canadensis</i>	Buffaloberry	Achenes	1	0.19	Dry calcareous open woods, banks
<i>Arctostaphylos uva-ursi</i>	Kinnikinnick	Seeds	9.5	1.78	Exposed rocks, river banks, eskers, sandplains
<i>Rubus</i> sp.	Raspberry	Nutlets	7	1.32	Moderately dry open forests, riverbanks
Graminoids:					
<i>Carex</i> sp.	Sedge	Achenes	190	35.68	Wet calcareous or acidic soils, meadows, riverbanks, ponds
<i>Eleocharis</i> sp.	Spikerush	Achenes	2	0.38	Calcareous sandy ponds, riverbanks
<i>Eleocharis palustris</i>	Common spikerush	Achenes	6	1.13	Sheltered margins of lake/ponds
<i>Scirpus</i> sp.	Bulrush	Achenes	1	0.19	Wet marshes, lake shores
<i>Scirpus validus</i>	Softstem bulrush	Achenes	4	0.75	Sheltered lake shores, water up to 1 m deep
Forbs:					
<i>Alisma</i> sp.*	Water plantain	Achenes	8	1.50	Marshy places, edges of sloughs
<i>Cicuta</i> cf. <i>maculata</i>	Spotted water hemlock	Fruits	2	0.38	Marshy lake shores, stream banks
<i>Chenopodium</i> sp. (type 1)	Goosefoot	Seeds	28	5.26	Moist saline areas, clearings
<i>Chenopodium</i> sp. (type 2)	Goosefoot	Seeds	1	0.19	
<i>Hippuris vulgaris</i>	Common mare's-tail	Fruits	1	0.19	Shallow ponds, lakes
Labiatae undiff.	Mint	Nutlets	1	0.19	
<i>Najas flexilis</i> *	Nodding water nymph	Seeds	1	0.19	Shallow fresh and brackish waters
<i>Polygonum lapathifolium</i>	Curlytop knotweed	Achenes	3	0.56	Wet lake shores
<i>Potamogeton</i> sp.	Pondweed	Achenes	14	2.63	Edge of shallow ponds, meadows, lakeshores, banks
<i>Potamogeton</i> cf. <i>foliosus</i>	Leafy pondweed	Achenes	2	0.38	Shallow still waters
<i>Potamogeton</i> cf. <i>gramineus</i>	Variableleaf pondweed	Achenes	1	0.19	Still waters, 0.5-3 m deep
<i>Potamogeton pusillus</i> *	Small pondweed	Achenes	1	0.19	Quiet waters up to 2 m deep
<i>Ranunculus</i> sp.	Buttercup	Achenes	1	0.19	Calcareous shallow ponds
<i>Potentilla palustris</i>	Purple marshlocks	Achenes	3	0.56	Wet marshes, bogs
<i>Mitella nuda</i>	Naked	Seeds	2	0.38	Cold boreal forest

	miterwort				
<i>Sparganium</i> sp.	Bur-reed	Achenes	1	0.19	Shallow ponds, bog pools, lakes
<i>Typha latifolia</i>	Common cattail	Achenes	165	30.99	Wet moist places
Unknowns:					
Type 1			5	0.94	
Type 2			7	1.32	
Total			532.5	100	

Note: Habitat descriptions and plant nomenclature follows Cody (1996) and Montgomery

(1977)*.

Table 2.3: Bryophytes from Dalton Highway bridge site

Moss Taxa	Samples							Preferred Habitat
	SR05-DH1	SR05-DH2	SR05-DH3	SR05-DH4	SR05-DH5	SR05-DH6	SR05-DH7	
<i>Amblystegium serpens</i>		-	+	+		+		Terrestrial wet - dry trees, wood, rock, soil, humus
<i>Barbula convoluta</i>				+				Terrestrial wet - dry soil, rock, trees, wood, rock, soil, humus
<i>Brachythecium starkei</i>			+					Terrestrial mesic - dry wood, rock, soil, humus
<i>Brachythecium</i> sp.				+	+			
<i>Bryum</i> sp.				+	+	+		
<i>Calliergon giganteum</i>			+	+	+	+	+	Aquatic emergent or submerged peat, humus
<i>Calliergon richardsonii</i>			+			+	+	Aquatic emergent or submerged peat, humus
<i>Calliergon stramineum</i>					+	+		Aquatic emergent peat, humus, wood, rock, soil, humus
<i>Ceratodon purpureus</i>			+					Terrestrial wet - dry wood, rock, soil, humus
<i>Dicranum acutifolium</i>			+					Terrestrial mesic - dry wood, rock, soil, humus
<i>Dicranum undulatum</i>			+					Terrestrial wet - mesic wood, peat, humus
<i>Drepanocladus aduncus</i>			+	+		+	+	Emergent or submerged soil, peat, humus
<i>Hylocomium splendens</i>		+	+		+			Terrestrial wet - mesic wood, rock, soil, humus
<i>Hypnum pratense</i>						+		Terrestrial wet soil, peat, humus
<i>Leptobryum pyriforme</i>				+				Terrestrial wet - mesic wood, rock, soil, humus
Mniaceae <i>Plagiomnium ellipticum</i>				+	+			Terrestrial wet peat, humus

<i>Rhytidium rugosum</i>								Terrestrial dry	rock, soil
<i>Scorpidium scorpioides</i>							+	Aquatic submerged or floating	peat, humus
<i>Warnstorfia</i> sp.	+	+	+	+	+	+	+	Aquatic emergent or submerged	peat, humus

Note: Identification, habitat description and plant nomenclature follows Nyholm (1954), Lawton (1971), Steere (1978), Crum and Anderson (1981) and Smith (1993). + = present and *=addition from 2002 samples.

Table 2.4: Plant macrofossil abundances

Sample & Fraction	Mosses	Roots/Organics	Bark	Leaf Fragments	Large Wood	Small Wood	Seed Covers	Seeds	Bones	Stem Parts	Insect Remains
SR05-DH7 > 2 mm	5	x	1	x	x	x	x	x	x	5	x
SR05-DH7 > 1.18 mm	5	x	x	x	x	x	x	3	x	5	x
SR05-DH6 > 2 mm	2	x	2	x	2	x	x	x	x	3	x
SR05-DH6 > 1.18 mm	2	x	2	1	3	1	x	1	x	5	x
SR05-DH5 > 2 mm	3	2	4	1	5	2	2	1	x	3	1
SR05-DH5 > 1.18 mm	3	x	3	1	4	2	1	1	x	3	1
SR05-DH4 > 2 mm	3	2	4	1	5	1	1	1	x	4	1
SR05-DH4 > 1.18 mm	2	x	3	1	3	1	1	1	x	3	1
SR05-DH3 > 2 mm	3	3	5	2	5	1	3	1	x	4	1
SR05-DH3 > 1.18 mm	2	1	3	1	3	1	1	2	x	3	1
SR05-DH2 > 2 mm	x	1	x	x	1	1	x	x	x	2	x
SR05-DH2 > 1.18 mm	1	1	1	x	1	2	x	x	x	2	1
SR05-DH1 > 2 mm	1	x	1	x	2	2	x	x	1	2	x
SR05-DH1 > 1.18 mm	1	1	2	x	2	2	x	x	x	2	x

Notes: X= absent, 1= trace, 2= present, 3= common, 4= frequent, 5= abundant. Ratings based on abundance of macrofossils in Petri dish. Seed

covers comprise mainly *Carex* sp. perigynia.

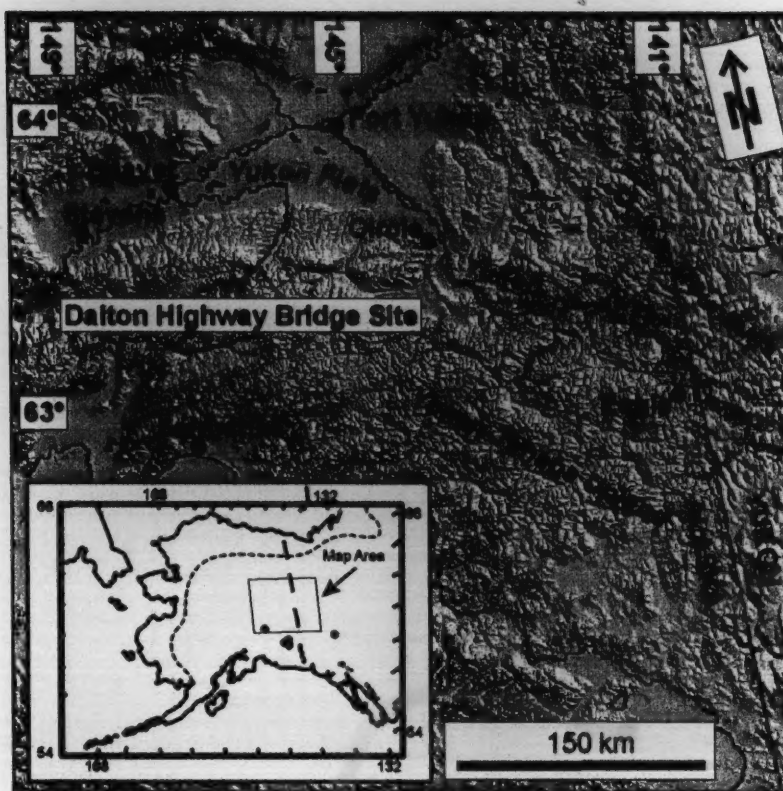


Figure 2.1: Location of Dalton Highway bridge site in central Alaska. The dashed line on the inset map indicates the modern northern limit of *Castor canadensis* (after Jenkins and Busher, 1979); dots on the inset map are occurrences of living *Typha latifolia* (after Porsild and Cody, 1980).

Figure 2.2: Stratigraphy, chronology and plant macrofossil assemblage at the Dalton Highway bridge site with sample locations.



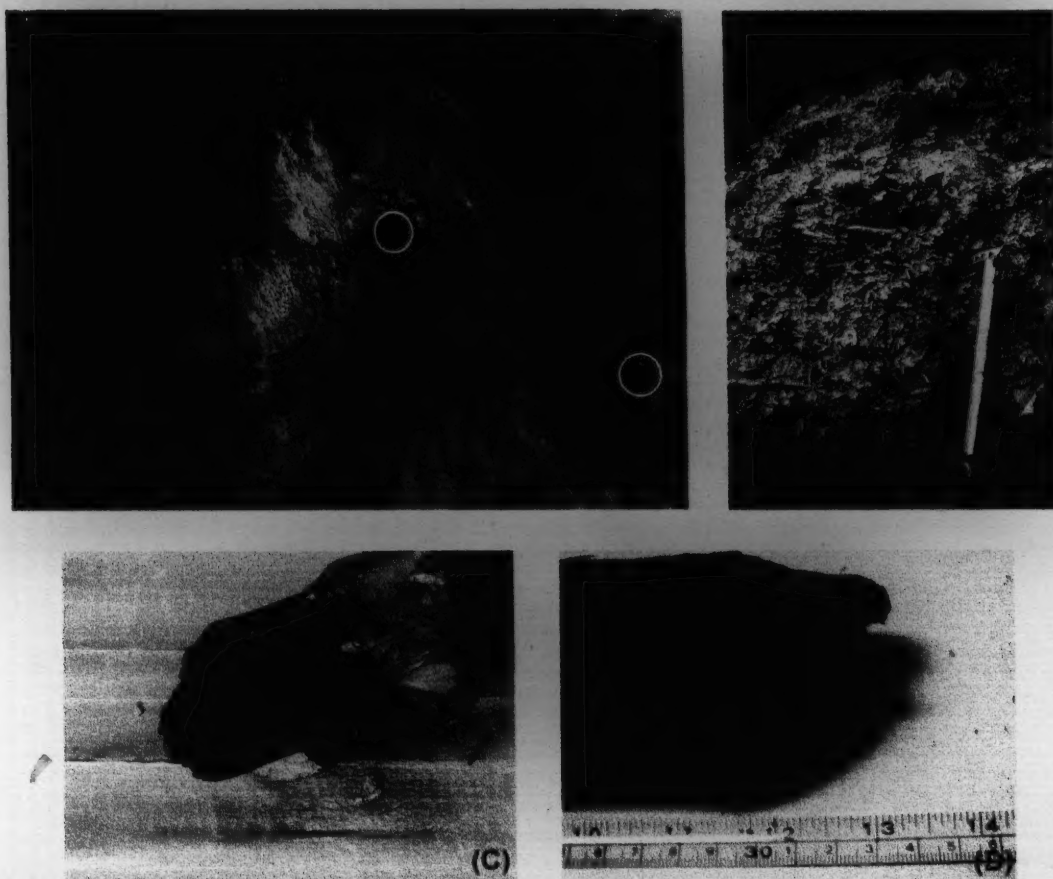


Figure 2.3: (A) Study site with location of beaver dam (arrowed) near top of bluff, ca. 50 m above river level. Note people for scale (circled). (B) Beaver dam with abundant chewed wood and twigs. Ice axe is 80 cm long. (C) and (D) Close-up photos of beaver-chewed wood.



Figure 2.4: Selected SEM images of plant macrofossils found in the assemblage. (A) *Najas flexilis*, (B) *Typha latifolia*, (C) *Eleocharis palustris*, (D) *Scirpus validus*, (E) *Potamogeton* sp., and (F) *Betula glandulosa*.

2.7 References

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CHAPTER 3 - LATE PLEISTOCENE SPRUCE MACROFOSSILS AND POLLEN: IMPLICATIONS FOR THE HISTORY OF SPRUCE IN ALASKA AND YUKON TERRITORY

3.1 Introduction

The northern boreal forest of Alaska and Yukon Territory is characterized by white spruce (*Picea glauca*) and black spruce (*Picea mariana*). Yet, the origin of these spruce (*Picea* spp.) populations in eastern Beringia (unglaciated Alaska and Yukon) is poorly understood. Two hypotheses have been proposed to account for the apparent distributional history of spruce as it is derived from paleoecological records. The first proposes that spruce did not survive in eastern Beringia during the Last Glacial Maximum (LGM) but instead re-colonized the region by migrating from a refugium south of the Laurentide Ice Sheet (Hopkins et al., 1981; Ritchie and MacDonald, 1986; Carlson and Finney, 2004). This hypothesis is largely based on low spruce pollen percentages (<2%) and a lack of radiocarbon dated spruce macrofossils during this interval. The second suggests that spruce survived the LGM within the northern refugium of eastern Beringia in small populations, re-expanding following amelioration of climate (e.g. Brubaker et al., 2005). This model is based on an alternate interpretation of low spruce pollen percentages, unrealistic plant migration rates from proposed southern refugia (Abbott et al., 2000b; Brubaker et al., 2005) and, increasingly, genetic evidence from extant populations (Alden and Loopstra, 1987; Anderson et al., 2006).

The vegetation of interior Alaska during the late Pleistocene – early Holocene (LP-EH) changed from herb-tundra (> 12,000 ^{14}C yrs BP) to birch-shrub tundra (12,000 – 10,000 ^{14}C yrs BP) to boreal forest that included white spruce (8,500 ^{14}C yrs BP), followed by black spruce (6,000 ^{14}C yrs BP) (Edwards et al., 2001). The expansion of white spruce is correlated to a warm, moist

early Holocene climate, where rising lake-levels suggest increased effective moisture (Bigelow, 1997; Abbott et al., 2000a and Edwards et al., 2001). The arrival of spruce in interior Alaska seems to vary from site to site, and is dependent on the availability of suitable micro-habitats, with white spruce favouring well-drained sites. The Tanana valley to the south-east records the earliest spruce pollen increase in Alaska, with ages ranging from 9,500 – 9,000 ^{14}C yrs BP (Ager, 1975; Hu et al., 1993) and the earliest spruce macrofossils in Alaska at ca. 9,400 ^{14}C yrs BP (Weber et al., 1981). The appearance of spruce in southeast and interior Alaska suggests that the Tanana and Yukon River valleys were major corridors for spruce migration (Hopkins et al., 1981; Carlson and Finney, 2004). The earliest spruce pollen increases identified from records along the Porcupine River valley are ca. 8,700 ^{14}C yrs BP at Tiinkdhul Lake (Anderson et al., 1988) and ca. 8,500 ^{14}C yrs BP at Ped Pond (Edwards and Brubaker, 1986). These bulk-sediment ages have been used to discount the Porcupine River as a major corridor of migration (Carlson and Finney, 2004). The timing of spruce arrival in central Alaska is still debated, but a general consensus is that white spruce was growing locally in lowland areas by 8,500 – 8,000 ^{14}C yrs BP and well established across most of the landscape by 6,500 ^{14}C yrs BP (Bigelow and Edwards, 2001). The decline of white spruce and expansion of black spruce between 7,000 – 5,000 ^{14}C yrs BP suggests either a slight cooling trend during the mid Holocene (Hu et al., 1993; Edwards et al., 2001) or an increase in cool, waterlogged soils, which hampered the spread of white spruce (Anderson et al., 1990). By 5,000 ^{14}C yrs BP, black spruce dominated northern Alaska with white spruce the dominant conifer taxon in western Alaska (Anderson and Brubaker, 1994).

The arrival or local presence of spruce in eastern Beringia is based primarily on the interpretation of pollen records obtained from lacustrine sediments (e.g., Ritchie and Hare, 1971; Ritchie, 1982; MacDonald, 1987). Often, radiocarbon dates from lacustrine records are derived from bulk sediment or aquatic macrofossils and, depending on surrounding bedrock and water geochemistry, these can be subject to hardwater or old carbon contamination (MacDonald et al,

1991; Abbott et al., 2000a), increasing the apparent age by several centuries or considerably more. For example, Bigelow and Edwards (2001) record spruce pollen (>10%) in central Alaska at ca. 8300 ^{14}C yrs BP, which is 1000 years older than the arrival of spruce at a nearby site, Eightmile Lake (Ager, 1983). Abbott and Stafford (1996) show it can be difficult to detect the initial arrival of plant taxa through pollen records, primarily because of the differing possible interpretations of low pollen percentages. These could indicate the presence of plants, such as spruce, whose pollen tends not to be widely dispersed from the parent plant. Conversely, very low percentages of pollen can reflect merely fortuitous long distance dispersal events, an effect that is exacerbated if local vegetation, such as tundra, is producing only small amounts of pollen. Generally, therefore, pollen analysts have used a >10% threshold as indicative of the local presence of spruce (Anderson and Brubaker, 1986; Bigelow and Powers, 2001). Plant macrofossils, however, are much better indicators of local presence of plants because their dispersal is more limited and importantly, plant macrofossils can be identified to a lower taxonomic level (Birks and Birks, 2000).

This paper presents new pollen and plant macrofossil data from paleosols spanning the LP-EH, exposed in cut banks along the Yukon River in the Yukon Flats, interior Alaska. New findings include spruce macrofossils from a mixed assemblage dated at 18,400 ^{14}C yr BP and spruce macrofossils associated with a paleosol dated at ca. 10,700 ^{14}C yr BP. We compare this new information with other spruce macrofossil and pollen records from northwestern North America, and discuss its significance for late Quaternary spruce history.

3.2 Study location and setting

The Yukon Flats is a lowland region extending 30,000 km² from the Tintina fault to the Brooks Range in the unglaciated region of central Alaska (Figure 3.1). Late Tertiary subsidence of the

Yukon Flats Sedimentary Basin (YFSB) produced up to 3 km of sedimentary fill, on which the Yukon River flows today (Williams, 1962; Dover, 1994; Kirschner, 1994). The surficial sediments of the Yukon Flats, to a depth of ca. 30 metres, consist of eolian sand sheets and loess overlying fluvial gravels, which, collectively, overlie Pliocene fine-grained sediments (Froese et al., 2005). The fluvial gravel – sand overbank contact is near modern river level and late Pleistocene ages from this level suggest a lack of recent vertical change along the Yukon River in the region (Froese et al., 2005).

Climate of the Yukon Flats is subarctic and continental due to the rain shadow effect of the Brooks Range to the north and the Alaska Range to the south, resulting in warm summers and cold, dry winters. At Fort Yukon (Figure 3.1) for the period 1938-1990, the mean July temperature was 17°C while the mean January temperature was – 28°C. Average annual precipitation at Fort Yukon (1938-1990) was 170 mm, with most falling between June and September. Average annual total snowfall was 1064 mm, with most falling between October and March (Western Regional Climate Center, 2007).

The vegetation of the Yukon Flats is dominated by northern boreal forest. White spruce prefers well-drained warm, south facing slopes and occurs with balsam poplar (*Populus balsamifera*) and paper birch (*Betula neoalaskana*) trees (Furrow, 1993), and rose (*Rosa* spp.), alder (*Alnus* spp.) and willow (*Salix* spp.) shrubs (Viereck et al., 1992). Sage (*Artemisia frigida*) and grasses are significant components of the ground vegetation. Black spruce prefers poorly drained, north-facing slopes with stands of larch (*Larix laricina*) and paper birch. *Sphagnum* spp. mosses, sedges (*Carex* spp.), grasses and ericaceous shrubs are components of the ground cover (Viereck et al., 1992). In the confines of the Yukon River valley, willow shrubs are common on newly deposited bar surfaces, and islands are dominated by white spruce, associated with taliks (Viereck et al., 1992). The modern soils of the Yukon Flats are Inceptisols and Gelisols (Muhs et al., 1998).

The Purgatory and Stevens sites (Figure 3.1) are located within a region of discontinuous permafrost with ice wedges exposed along eroding river bluffs. The Yukon River flows to the southwest, with up to two meandering channels, and up to three slough channels at the margins of the river (Froese et al., 2005). The Purgatory site (66°14'N, 148°16'W) is on the north side of the river, 20 km upstream from the village of Beaver, while the Stevens site (65°59'N, 148°57'W) is located on the south side, 5 km east of Stevens Village, which marks the approximate western edge of the Yukon Flats.

3.3 Methods

Several paleosols exposed at Purgatory and Stevens sites, are interbedded with eolian and loess deposits. Each paleosol horizon was described following the Canadian System of Soil Classification (Soil Classification Working Group, 1998) for dimensions, Munsell colour, texture, structure and horizonation. Nomenclature of the paleosols in the text refers to the US soil taxonomy system (Soil Survey Group, 1999). Sediment samples were collected at a vertical resolution of 10 cm for pollen and less than 50 cm for plant macrofossils, which covered all major paleosols and eolian deposits. Exposures were excavated to frozen ground (one to two metres) and fresh samples were collected from a vertical face using a trowel. Wood remains (1 – 10 cm in length) from paleosols and eolian sand sheets were recovered for radiocarbon dating. In this study, paleosols are listed in chronological order.

Subsamples of approximately 1 cm³, collected from sediment samples, were processed to concentrate pollen following conventional methods (Faegri and Iversen, 1989). Pollen counting was carried out by Schweger using a target pollen sum of 300 grains.

Macrofossils were extracted from sediment samples following the procedure outlined in Beaudoin (2007). Subsamples of 50 ml were measured by water displacement and sieved through a 0.09 mm mesh screen with water; some samples of up to 2 L were also sieved later, in an effort to increase macrofossil recovery. The remaining materials were screened through stacked 2.0, 1.18, 0.5, 0.25, 0.125 and 0.09 mm mesh screens with water, and then separated into morphological groups using a binocular dissecting microscope. Abundance of each morphological group was estimated using total coverage in Petri dish with 1 for rare and 5 for abundant. Seeds, achenes, nutlets and samaras, hereafter generalized as "seeds", were identified to the lowest taxonomic level possible. Identification of seeds was aided by comparison with modern samples from the Quaternary Environments Laboratory and Herbarium at the Royal Alberta Museum, and literature including Montgomery (1977), Porsild and Cody (1980) and Cody (1996).

Some plant macrofossils identified to genus or species level were selected for radiocarbon dating along with *in situ* wood fragments. All radiocarbon ages have been calibrated to calendrical ages (in yrs BP) using Oxcal v 3.10 (Bronk Ramsey, 2005).

3.4 Results

Purgatory Site

Stratigraphy

Lateral erosion by the Yukon River exposes cut-banks of eolian sand sheets, which form the broad, unscrolled surface of the Yukon Flats (Williams, 1962; Froese et al., 2005). The Purgatory

site (Figure 3.2) is an example of this Pleistocene surface and includes a laterally extensive paleosol interbedded within eolian deposits. The 8.5 metre high exposure from river level to modern soil is divided into four stratigraphic units (Figure 3.3): a lower unit of fluvial gravel (0-2.8 m) consisting of fluvial gravel clasts ranging from 1 cm to 7 cm in diameter, supported by a sandy-silt matrix; an eolian unit (2.8-4.6 m) consisting of cross-bedded and horizontal-stratified sand with paleowind directions from 200° - 220° (Figures 4 a-c). Small rootlets are common and suspected caribou dung (Figure 3.4 d) was found. A large shrub in growth position extends throughout the unit (Figure 3.4 e). A paleosol (Soil 1) (4.6-5 m) locally divided into three organic layers continues laterally across the exposure for ca. 135 m (Figure 3.2, Table 3.1 and Figure 3.4 f). An eolian deposit (5-8.5 metres) of well-sorted, cross bedded and horizontal stratified medium sands with small wood and rootlets overlies the paleosol. Soil 1, a Turbel (Soil Survey Group, 1999), is heavily cryoturbated into one to three organic layers depending on locality. The first Ah layer is 1-7 cm thick, gleyed with shrubby wood in growth position. The lower contact undulates with the underlying eolian deposit, which grades to a humic silt/organic clay-gleyed sediment. The bottom organic layer (3-5 cm thick) has a wavy appearance with discontinuous organic material extending >10 cm into the underlying sandy silt (Figure 3.4 f).

Plant macrofossils

At Purgatory, only the paleosol (Soil 1) contained several varieties of plant macrofossils, while no identifiable plant material was recovered from the underlying or overlying sand sheets (Table 3.2 and Table 3.3). In the lowest organic horizon of the paleosol, covered by samples SR05-G10 and SR05-G37, the dominant taxon is *Salix* sp., only three Salicaceae seeds and one *Populus* sp. seed were recovered after sieving several litres of sample. Within the same paleosol, the middle and upper horizons, SR05-G13 and SR05-G38, respectively, yielded a variety of different plant macrofossils including two needle fragments of *Picea* sp., two macrofossils of *Picea* cf. *glauca*

including part of a seed wing and a full needle (Figure 3.5 a-c), Betulaceae seeds, *Betula* cf. *glandulosa* samara, Salicaceae seeds, *Salix* sp. seeds, and Rosaceae seeds. Intact *Ledum* sp. leaves along with Ericaceae leaf fragments were also found. Only one *Anemone* sp. seed and one Gramineae caryopsis were found representing forbs and grasses. While not a highly productive site, the Purgatory paleosol (Soil 1) yielded evidence for trees and shrubs

Picea macrofossils

The two needle fragments from SR05-G38 (Soil 1) were initially identified to *Picea* sp. based on the four angled cross-section following Weng and Jackson (2000). We attempted to refine the identification to species level by comparing needle cross-sections of the subfossil material with cross sections of modern *Picea glauca* and *Picea mariana* needles from herbarium specimens (accession no: S214). Unfortunately, the needle fragments from the Purgatory site (Figure 3.5 a and b) were too compressed and distorted to allow a clear species-level attribution to be made. The full needle found in SR05-G38 was identified to *Picea* cf. *glauca* based on needle morphology and the presence of one resin duct. Modern *Picea glauca* needles have discontinuous resin ducts on both sides of the vascular bundle and rarely cross while *Picea mariana* has continuous resin ducts on both sides of the vascular bundle (Weng and Jackson, 2000). The needle from Purgatory was dissected and examined for number and configuration of resin ducts. Several dissections were performed and some needle fragments were examined by SEM (Figure 3.5 d-g). When cross-sections were not able to resolve species level identifications, needle apex shape was examined. *Picea mariana* needles generally have a blunt apex, compared to the sharp apex of *Picea glauca* needles (Figure 3.5 d and e) (Weng and Jackson, 2000). Several needles from different localities were collected from the Herbarium (*Picea glauca*: B97.5.85, B89.10.191, B93.55.9 and B84.1.358 and *Picea mariana*: B97.5.64) at the Royal Alberta Museum for comparison (Figure 3.5 d and f). Though the collections revealed variable apex morphology for

both species, the majority of reference needles show a blunt apex for *Picea mariana* and a sharp apex for *Picea glauca*, confirming Weng and Jackson (2000) findings. The *Picea* sp. seed wing found in SR05-G38 was compared with modern wings (accession no: S214) and, based on size and shape of the indent, it is referred to *Picea glauca* (Figure 3.5 c).

Pollen

The Purgatory site yielded one countable sample (SR05-G13), 25 cm above the paleosol within the overlying sand sheet, with only 108 grains counted, 26% of which are *Picea* (Table 3.2). *Picea* pollen was the highest percentage at Purgatory followed by Cyperaceae (20%), *Salix* (19%) and *Betula* (17%). Even though the pollen sum is low, the analysis indicates the local presence of trees and shrubs, reinforcing the reconstruction of local vegetation derived from the macrofossil assemblage.

Radiocarbon ages

Five radiocarbon dates have been obtained from the Purgatory site (Table 3.4 and Figure 3.3). Two new dates are reported in this paper and three have been reported from previous work at the site (Clement, 1999; Froese et al., 2005) (Table 3.4). The underlying sand sheet is dated at $11,550 \pm 70$ ^{14}C yrs BP (WAT 4100), $11,500 \pm 100$ ^{14}C yrs BP (WAT 4160) and $11,420 \pm 60$ ^{14}C yrs BP (Beta 214272). A wood macrofossil from Soil 1 (Figure 3.4 f), where the spruce macrofossils were recovered, is dated at $10,710 \pm 60$ ^{14}C yrs BP (Beta 214272) and the overlying sand sheet is dated at $10,270 \pm 25$ ^{14}C yrs BP (UCIAMS 28210).

Stevens site

Stratigraphy

The Stevens site (Figure 3.6) is a 14.5 metre high exposure from river level to modern soil composed of loess, interbedded with seven organic layers, identified as paleosols and described in Table 3.1 and Figure 3.7. The majority of these paleosols have A, B and C horizons, with evidence of cryoturbation (i.e., frost cracks and ice wedge casts) (Figure 3.8 a and b). The lower part of the exposure (0 – 2.5 metres) is dominated by laminated silt and clay with rare organic detritus. Layers of interbedded clay and silt occur between 2.5-4.9 metres (Figure 3.8 c) and the layers contain syngenetic frost cracks, which are predominantly infilled with clay-rich material (Figure 3.8 b).

Two prominent clay-rich horizons occur at 3.5 and 4 metres (Figure 3.7). The first horizon is composed of clayey-silt and surrounded by wood fragments and rootlets. The second horizon contains more silt and is lighter in colour. No cross-bedding is seen in the lower units, rather they consist of laminated silt and clay with rare organic detritus.

The lowest horizon at the Stevens site that I consider to be a paleosol is the horizon at 5.2 m (Soil 2) (Figure 3.6). This level and six overlying paleosols mark a change in sedimentation at the site from largely horizontally bedded silt and clay with finely laminated beds. From Soil 2 (5.2 m) to the modern surface sediments are largely sandy-silt (loess) with discontinuous or very thin Ah horizons and rare woody plant material in growth position. Most of the paleosols identified as such, on the basis of clearly-defined horizons, with significant lateral continuity (> 5 m), showed evidence of cryoturbation (frost cracks).

Soil 2 (Figure 3.8 d) has three distinct Ah horizons and woody plant material in growth position (up to 7 cm long). A small ice-wedge cast is present in the bottom horizon (26 cm deep and 6 cm wide) and frost cracks also occur (Figure 3.8 a and b). These two features, which are both epigenetic, and the undulating organic layers, suggest strong cryoturbation. Soil 3 (Figure 3.8 e) at 6.2 metres shows weak signs of cryoturbation compared to Soil 2, though two thin organic layers are evident with syngenetic frost cracks. Soil 4 (Figure 3.8 f) at 6.9 metres has thicker organic layers compared to Soil 3 and abundant wood fragments. Smaller wedge casts (up to 10 cm deep and 5 cm wide) are evident at the top of the soil. Soil 5 (Figure 3.8 g) at 9.3 metres has distinct planar A and C horizons with rootlets extending 10 cm below the Ah layer. Soil 6 (Figure 3.8 h) at 11.2 metres has thinner organic layers (< 2 mm), which are discontinuous and wavy in appearance. The B and C horizons are mottled and frost cracks and small wedge casts are evident. The aforementioned soils, based on horizons and strong cryoturbation, meet the criteria for Gelisols or Turbels (Soil Survey Group, 1999).

The most-developed paleosols at Stevens are Soils 7 and 8. Soil 7 (Figure 3.8 i) at 12.5 metres has thicker, more distinct horizons than the lower paleosols. The organic layer is wood rich with tree stumps in growth position. The B horizon is up to 10 cm thick. There are no clear signs of cryoturbation. Soil 8 (Figure 3.8 j) at 12.8 metres is very similar to Soil 7 with extensive A and B horizons up to 5 cm thick. There is an ice-wedge cast in the B horizon (5 cm deep by 1 cm wide). Soil 7 and Soil 8 are likely to be Inceptisols (Soil Survey Group, 1999), which is the modern soil type in many areas of the Yukon Flats (Muhs et al., 1998). Between 12.8-14 metres is massive sandy silt with *in situ* spruce stumps extending up from the surface of Soil 8 (Figure 3.8 k).

Plant macrofossils

The Stevens macrofossil assemblage is more productive than Purgatory though numbers and diversity of macroremains are still generally low, especially within the loess deposits (Table 3.2 and Table 3.5). Two *Typha latifolia* seeds were recovered from lower loess deposits in SR05-H11. The record is sparse below the first prominent paleosol (Soil 2 at 4.9 metres) (SR05-H52) yet fieldwork in 2002 produced spruce needles near the gleyed horizons at 3.5 and 4 metres (Figure 3.7 and Table 3.4). Soil 2 (SR05-H52) contained the largest quantity of seeds at both Purgatory and Stevens with a number of graminoids and forbs including 24 *Carex* sp., 4 *Cicuta maculata*, 163 *Mentha* cf. *arvensis*, one *Geum* sp., and two *Typha latifolia* seeds. One *Chenopodium* sp. seed was found in the loess sample above (SR05-H57) while Soil 3 at 6.2 metres (SR05-H67) contained one *Carex* sp. seed, and one Polygonaceae undiff. seed. SR05-H100, covering Soil 4 at 6.9 metres, recorded the first appearance of shrubs at Stevens with three *Betula* sp. and seven *Betula* cf. *glandulosa* samaras.

The overlying loess deposit (SR05-H105) contained one *Hippuris vulgaris* seed. SR05-H173, covering Soil 5 at 9.3 metres, was more productive with six *Rubus* sp. seeds, one *Carex* sp. achene, 11 *Chenopodium* sp. seeds, three *Potentilla* sp. seeds, and three *Typha latifolia* seeds. In Soil 6 at 11.2 metres (SR05-H166), one *Arctostaphylos uva-ursi* seed and two *Rubus* sp. seeds were identified. In the overlying loess deposit (SR05-H162), the first appearance of *Picea* sp., was recorded in the form of one small needle fragment. The upper two paleosols at Stevens are the richest in macroremains from trees and shrubs. Only needle tips were identified and counted for *Picea* sp. Soil 7 at 12.5 metres (SR05-H158) contained one *Picea* sp., 38 *Picea glauca*, two *Picea* cf. *mariana* needle tips and four *Betula* sp. samaras. Soil 8 at 12.8 metres (SR05-H157) contained similar macrofossils with 12 *Picea* sp., five *Picea* cf. *glauca*, 37 *Picea glauca* and eight *Picea* cf. *mariana* needle tips. SR05-H157 also contained 11 *Betula* cf. *glandulosa* samaras and one *Betula* cf. *papyrifera* samara, but no macroremains from graminoids or forbs.

Pollen

Pollen analysis at the Stevens site produced eight samples yielding more than 300 grains, with four other samples relatively close to this target (Figure 3.7). Soil 4 was the only paleosol at Stevens that did not contain pollen. The pollen assemblage was similar throughout Stevens with *Picea* between 10-20% in Soils 2 and 3, increasing to 30% by Soil 6. Even in the loess above Soil 6, *Picea* was recorded between 20-30%. The highest occurrence of *Picea* in the assemblage was in Soil 7 with 73%. Throughout Stevens, *Alnus* and *Betula* were important components, usually above 20%, but no higher than 50%. *Salix* pollen occurred throughout the assemblage but usually below 10%. High amounts (ca. 30%) of Cyperaceae were present in Soil 2 yet Cyperaceae and Ericaceae undiff. were minor components throughout Stevens site.

Radiocarbon ages

The Stevens site has 12 radiocarbon ages associated with Soils 2,5,6,7 and 8 (Table 3.4). The ages at Stevens provide a terrestrial chronology for the early Holocene in central Alaska from $9,830 \pm 130$ ^{14}C yrs BP (AA52060) to $6,950 \pm 80$ ^{14}C yrs BP (GSC-6735). A spruce needle dated at $18,700 \pm 440$ ^{14}C yrs BP (AA52063) and a woody fragment dated at $42,100 \pm 2,000$ ^{14}C yrs BP (AA52062), within the lower sediments of the Stevens site, are significantly older than the overlying chronology and are discussed later. The two sites combined provide a near continuous chronology from ca. 11,500 ^{14}C yrs BP to ca. 7,000 ^{14}C yrs BP.

3.5 Discussion

Late Pleistocene and early Holocene environments

The stratigraphy of the Purgatory river cut-bank suggests two contrasting environments. An eolian sand sheet, likely created during a cold and arid climate, was deposited at ca. 11,500 ^{14}C yrs BP and prior to ca. 10,700 ^{14}C yrs BP. The medium sand grains with horizontal stratification and cross-bedding suggest strong winds, moderate sediment supply, and possible seasonal variations of regional ice cementation and snow cover (Lea and Waythomas, 1990). Wood fragments and rootlets throughout the unit suggest a sparse vegetation cover along the Yukon River floodplain during the late Pleistocene in central Alaska. A large woody-shrub found *in situ* within the eolian sand sheet suggests that shrubby elements were present, and that sand aggradation was rapid.

Soil 1 overlying the eolian sand sheet dated at ca. 10,700 ^{14}C yrs BP records a marked change in environmental conditions. The paleosol records a period of stability, likely extending for 500-700 ^{14}C years, during which wind intensity had decreased and sand sheet aggradation had ceased. The paleosol is heavily cryoturbated and locally divided into three organic horizons ranging from 35-50 cm deep. This translocation of Ah horizons is common in periglacial conditions as a result of seasonal freeze-thaw (Pawluk, 1988; Smith et al., 1991; Sanborn et al., 2006).

The overlying sand sheet was deposited by about 10,300 ^{14}C yrs BP, based on dated wood, with a maximum age of ca. 10,700 ^{14}C yrs BP. Additional basal ages on sand sheets in the Yukon Flats of 10,250 ^{14}C yr BP, 10,300 ^{14}C yr BP and 10,500 ^{14}C yr BP (Froese et al., 2005) indicate regional sand sheet aggradation between 10,500 and 10,250 ^{14}C yr BP (Figure 3.9). The sand sheets indicate a return to strong winds, adequate regional sand supply and a colder, more arid climate. Rootlets throughout the unit suggest a sparse vegetation cover similar to that associated with the previous sand sheet. The overlying sand sheet is part of the eolian surface mapped by Williams (1962). A substantial modern soil with horizons up to 50 cm thick suggests the sand sheets have been stable through most of the Holocene.

Interestingly, the ages obtained from the eolian sand sheets and the paleosol at Purgatory coincide with abrupt climate oscillations recorded in the North Atlantic borderlands (Alley et al., 1997; Bond et al., 1997). The underlying sand sheet formed ca. 11,500 ^{14}C yrs BP (13,610 - 13,170 cal. yrs BP), which is concurrent with the latter stages of the cold, Older Dryas interval (13,540 - 13,350 cal. yrs BP) (Litt et al., 2001). The paleosol dated at ca. 10,700 ^{14}C yrs BP (12,860 - 12,650 cal. yrs BP) occurs during a warming trend around the North Atlantic, attributed to the Allerød interval (13,350 - 12,680 cal. yrs BP) (Litt et al., 2001). The overlying sand sheet signifies a return to colder times with stronger winds at ca. 10,300 ^{14}C yrs BP (12,150 - 11,840 cal. yrs BP), which occurs during the Younger Dryas chronozone (12,900 - 11,600 cal. yrs BP) (Litt et al., 2001). The terrestrial deposits at Purgatory site suggest that central Alaska was affected by climate changes broadly synchronous with climate oscillations identified in northwest Europe. The synchronicity between these North Atlantic events and the deposits at Purgatory has implications for the spatial scope of these climatic events. The current records of such oscillations in the North Pacific are growing, yet there are still relatively few available for comparison.

Plant macrofossils from the late Pleistocene soil at Purgatory provide a local record of vegetation at the Yukon Flats. At the Purgatory site, scarcity of plant macrofossils may suggest a sparse vegetation community. However, taphonomic effects, including humification and degradation of macrofossils, are likely to be influential at the site (Glaser, 1981). The most important plant macrofossils were found in the paleosol (Soil 1), dated at ca. 10,700 ^{14}C yrs BP. The macrofossils indicate presence of spruce trees with shrubs of birch, willow, Labrador tea and poplar. Forbs and grasses were also present, yet willow shrubs dominated the understory plants. Spruce was able to survive during this stable period, indicating favourable moisture availability and temperatures (Payette et al., 2001; Brubaker et al., 2005).

The small pollen sum at Purgatory suggests sparse vegetation, rapid deposition or influential post-depositional processes. However, even though only 108 grains were identified, 28 grains or 26% of them were spruce pollen, suggesting the presence of local spruce trees and not long distance transport. Relatively high percentages of birch and willow pollen (17 and 19%, respectively) support the macrofossil assemblage, adding further evidence for the presence of spruce trees with shrub elements of predominantly willow and birch.

The stratigraphy at the Stevens site indicates an alternating environment between stable periods of soil formation, and periods of rapid loess accumulation. In contrast to the Purgatory site, sediments at the Stevens site are predominantly fine sand and silt (loess), suggesting a lower energy environment. Wind intensity appears to have decreased in the early Holocene in comparison with late Pleistocene times. Chronology at the Stevens site indicates that this transition in wind intensity occurred after 10,200 ^{14}C yrs BP, the youngest age on regional sand sheets and before ca. 9,800 ^{14}C yrs BP, when Soil 2 formed.

Paleosols at the Stevens site represent short periods of stability when loess accumulation decreased. Most paleosols at Stevens show evidence of cryoturbation. Soil 2 has a wedge cast up to 26 cm deep and 6 cm wide while other paleosols contain smaller syngenetic frost cracks (Figure 3.8 a and b). The development of such features indicates thermal contraction events with exposure over several years. Ice wedge development usually occurs during cold, dry conditions, where precipitation is $<200\text{mm/yr}$ (Péwé, 1959; Murton et al., 2000). Soils 7 and 8 show thick organic layers with *in situ* stumps and well defined B and C horizons. These paleosols show modest signs of cryoturbation, but were likely formed during wetter conditions with boreal forest providing greater ground insulation. Loess accumulation ceased shortly after Soil 8, and conditions have stabilized to allow formation of a substantial ($> 50\text{ cm}$) modern Inceptisol.

The Stevens site represents vegetation from the early Holocene (ca. 9800 – 7000 ^{14}C yr BP). The macrofossil assemblage indicates that graminoids and forbs were abundant in the early Holocene with birch appearing at ca. 9,500 ^{14}C yr BP. Wetland taxa such as *Typha latifolia*, *Hippuris vulgaris* and *Potamogeton* sp. occur in loess samples. These aquatic macrofossils imply wetlands or small ponds on the local surface, indicating poor drainage, which are likely associated with shallow active layers during the early Holocene. Spruce trees dominate the local vegetation associated with the last two paleosols (Soils 7 and 8) at ca. 7000 ^{14}C yr BP with birch trees and shrubs as a secondary component.

Interestingly, spruce macrofossils were not recovered in the lower paleosols at the Stevens site, yet significant spruce pollen percentages are present (ca. 20%). The pollen assemblage records an area dominated by spruce and alder with an understory of birch and willow shrubs, while the plant macrofossil assemblage records forb/herb vegetation until the upper soils (7 and 8). The spruce pollen in these lower Stevens soils probably reflects the regional signal of spruce in the Yukon Flats at ca. 9,700 ^{14}C yr BP (Soil 2). Based on the morphology of the lower Stevens paleosols (Soils 2 – 6), spruce was unlikely to have colonized on these thinner substrates with a continual aggradation of loess. Soils 7 and 8 reflect a more stable time when spruce trees were local at the Stevens site. We suspect that the appearance of spruce macrofossils at the Purgatory soil (Soil 1) and the upper soils at Stevens (Soils 7 and 8) indicate sufficient soil development such that local spruce trees could grow on these surfaces, yet the thinner Turbels at Stevens could not support them.

Refugia in eastern Beringia?

The presence of spruce macrofossils in interior Alaska at ca. 10,700 ^{14}C yr BP has implications for post-glacial spruce migration. Records of spruce from 42 sites in northwestern North

American (Table 3.6) were rated based on chronological reliability. For example, if a spruce macrofossil is directly AMS dated at one site, then a high confidence rating is assigned. In contrast, if spruce pollen rise is correlated with a bulk lacustrine radiocarbon date at a site, then a lower confidence rating is assigned. This system assumes that plant macrofossils record the local presence of spruce, while pollen percentages (>10%) may record local or regional inputs. The majority of records are pollen percentages associated with lacustrine bulk dates (Table 3.6 and Figures 3.10 and 3.11).

Spruce macrofossils have been recovered from organic detritus dated between 15,900 – 13,500 ^{14}C yrs BP (Figure 3.10, sites 2-3) in the Bell Basin of north-central Yukon. However, the reliability of these macrofossil dates have been questioned (Hopkins et al., 1981). Similar detrital organics were recovered from the Stevens site. Spruce needles dated by accelerator mass spectrometry at $18,700 \pm 440$ ^{14}C yrs BP, (AA52063) (Table 3.4 and Figure 3.10, site 1) found in the lower sediments of a site 300 metres downstream from Stevens, are considerably older than the rest of the chronology. As these are AMS dates on a few spruce needles, they should be reliable. However, a wood fragment from the same deposit has an age of $42,100 \pm 2,000$ ^{14}C yrs BP. The origin of the bedded silts and clays that host the detrital macrofossils, including the dated spruce needles is not entirely clear, but the fine laminations suggest lacustrine, or more likely, an abandoned channel of the Yukon River. Given this setting, we cannot be certain how far these were transported. We suspect these may be relatively local given their concentrations.

The earliest post glacial spruce in northwestern North America, excluding the macrofossils mentioned above, occur before 11,000 ^{14}C yrs BP in northern Yukon and the Northwest Territories (Figure 3.10, sites 1-6). Substantial spruce pollen percentages from sites along the Porcupine River in north-central Yukon (Figure 3.10, site 4) (Lauriol et al., 2002) and in the Northwest Territories (Figure 3.10, site 6) (Ritchie and Hare, 1971) record local populations of

spruce at ca. 11,500 ^{14}C yrs BP. The spruce pollen rise ($> 20\%$) along the Porcupine River, near the Alaskan border, (Figure 3.10, site 4) (Lauriol et al., 2002) suggests that spruce was local about two thousand years before previous records of 8,700 ^{14}C yrs BP (Figure 3.10, site 28) (Anderson et al., 1988) and 8,500 ^{14}C yrs BP (Figure 3.10, site 31) (Edwards and Brubaker, 1986). Interestingly, the northern appearance of spruce is near-synchronous with the spruce pollen rise in areas south of the former Laurentide Ice Sheet, in central Alberta at ca. 11,500 ^{14}C yrs BP (Figure 3.10, site 7) (Lichti-Federovich, 1970). Generally, first occurrence dates for spruce pollen in records from northern Alberta are closer to 11,000 ^{14}C yrs BP (Figure 3.10, sites 8-9) (Ager, 1975; Vance, 1986).

The earliest post-glacial spruce in Alaska, excluding the older needles at Stevens, is from Birch Lake, central Alaska (Figure 3.10, site 10) at 10,900 ^{14}C yrs BP (Ager, 1975), but other records from Birch Lake suggest that spruce arrived between 9,500 – 8,500 ^{14}C yrs BP (Figure 3.10, sites 16 and 35) (Ager, 1975; Bigelow, 1997). Abbott et al. (2002) report AMS dates from Birch Lake and found that Ager's (1975) spruce rise was too old, by ca. 400 ^{14}C yrs. The divergence of ages illustrates the problems of lacustrine chronologies and the effect of "old" carbon in Arctic lakes (Abbott and Stafford, 1996; Abbott et al., 2000). Given the uncertainties, the spruce macrofossils from Purgatory at 10,710 ^{14}C yrs BP (Figure 3.10, site 11) seem to be the earliest known post-glacial spruce remains in Alaska. The next earliest spruce following Purgatory occurs at Wien Lake at ca. 9,500 ^{14}C yrs BP (pollen rise) (Figure 3.10, site 17) (Hu et al., 1993) and Canyon Creek in central Alaska at $9,460 \pm 155$ ^{14}C yrs BP (plant macrofossil) (Figure 3.10, site 19) (Weber et al., 1981). Spruce is generally local in southeast Alaska around 9,000 ^{14}C yrs BP and by 8,500 – 8,000 ^{14}C yrs BP, is local in central Alaska and central Yukon (Figure 3.10).

The efficiency of seed dispersal, the availability of suitable sites and the quantity and longevity of source plants determine a species migration or range extension rate (Ritchie, 1984). Ritchie and

MacDonald (1986) estimate post-glacial migration rates of spruce in western Canada at ~ 2 km/ ^{14}C yr, promoted by strong southerly winds and rapid seed dispersal across open, flat plains. Hopkins et al. (1981) suggest a rate of ~ 1 km/ ^{14}C yr based on spruce pollen records from the Great Slave Lake, Northwest Territories, and the Mackenzie Delta region. This rate is four times faster than estimated migration rates for post-glacial spruce in eastern Canada (Davis, 1981). Yansa (2006) calculated late Pleistocene spruce migration rates of 0.38 km/ ^{14}C yr (0.30 km/yr) for the northern Great Plains region of USA and Canada. This estimate is similar to other Holocene range extensions of spruce (0.1 – 0.5 km/ ^{14}C yr) (Grimm and Jacobson, 2004). If spruce macrofossils at Purgatory (Figure 3.10, site 11) originated from the south, from a refugium in the continental United States, then migration rates would have to be significantly faster than those proposed by Hopkins et al (1981) and Ritchie and MacDonald (1986). If we assume that Lofty Lake in Alberta (Figure 3.10, site 7) (Lichti-Federovich, 1970) represents the earliest local spruce at 11,500 ^{14}C yrs BP, which migrates to Whitehorse in the southern Yukon by 11,000 ^{14}C yrs BP, then the required rate to reach Purgatory is 3 to 3.5 km/ ^{14}C yr. This rate assumes that spruce would migrate along the Yukon River through central Yukon, and into interior Alaska. Even when calibrating these ages, the migration rates remain too high. Assuming that spruce is local in southern Yukon (Whitehorse) at 11,000 ^{14}C yrs BP (12,960 – 12,880 cal. yrs BP) which reaches Purgatory at 10,710 ^{14}C yr BP (12,860 – 12,650 cal. yrs BP), then the migration rates range from 2.5–45 km/yr. Both the radiocarbon and calibrated ages suggest that migration rates are unrealistic for spruce to migrate from the south, when compared to recent estimations (Yansa, 2006). However, it is not uncommon to find seeds, whole trees and branches of white spruce transported downstream in the Mackenzie River (Ritchie, 1984). If spruce reaches the Upper Mackenzie River in such a way, then this may account for faster migration rates.

Alternatively, there are tantalizing hints that spruce may have survived in refugia in northern Canada (Figure 3.10, sites 2–6). The existence of spruce refugia in eastern Beringia has

previously been rejected based on a scarcity of spruce plant macrofossils during the LGM and low spruce pollen percentages (Hopkins et al., 1981). New spruce macrofossils dated between 26,000 – 24,000 ^{14}C yrs BP at the onset of the LGM have been discovered in central Yukon (Zazula et al., 2006), and a significant spruce pollen percentage rise occurred at ca. 27,000 ^{14}C yrs BP in southwest Yukon, though based on bulk lacustrine ages (Rampton, 1971). The macrofossils suggest that spruce was able to adapt and sexually reproduce, in an environment characterized by arid conditions and cold temperatures (Zazula et al., 2006). In addition to the macrofossil evidence, genetic evidence based on spruce chloroplast DNA suggests a refugium within Alaska, dismissing the southerly migration model (Anderson et al., 2006). If the Purgatory spruce macrofossils and pollen rise, associated with an age of ca. 10,700 ^{14}C yrs, originated from refugia in northern Canada, it is estimated that migration rates would be 0.07 – 0.18 km/ ^{14}C yr, based on a route via the Porcupine and Yukon River valley systems. To explain the rapid dispersion of spruce in north and south locations, simultaneous re-population from two main sources (i.e. southerly and refugial), as previously suggested (Matthews, 1970, 1976; Hopkins et al., 1981; Raup and Argus, 1982), may have occurred.

Pollen vs. Plant macrofossils for detecting cryptic refugia

Trace amounts of spruce pollen (<5%) are recovered from LGM lake sediments in eastern Beringia, but whether they are from local tree sources is hard to interpret (Brubaker et al., 2005). Some studies use a target threshold of >10% to account for local presence (Anderson and Brubaker, 1986; Bigelow and Powers, 2001). Brubaker et al. (2005) suggest that these small pollen percentages likely reflect local populations based on 1) no evidence of south to north decline in *Picea* pollen during the 21,000 - 19,000 cal. yrs BP interval, which would indicate long distance transport from temperate localities; 2) the exclusive occurrence of *Picea* pollen in eastern Beringia and *Pinus* pollen in western Beringia, in comparison to windblown (regional)

inputs of pollen from temperate forest latitudes in Asia and North America; and 3) greater abundance of *Picea* pollen in eastern Beringia compared to *Pinus* pollen (Brubaker et al., 2005). The existence of a spruce refugium has previously been discarded based on low percentages of pollen and a lack of macrofossils (Ritchie and MacDonald, 1986; Hopkins et al., 1981), yet in the case of Purgatory and Stevens, we see evidence of both, indicating local plant populations. Future interpretations of spruce pollen during MIS 2 in eastern Beringia should identify the problems of detecting cryptic refugia, recognizing that the incorporation of plant macrofossil studies can significantly enhance the likelihood of detecting refugia.

3.6 Conclusions

The record presented here suggests that spruce survived locally in central Alaska or in cryptic refugia in northwestern Canada. This suggestion is based on a new record of spruce macrofossils and pollen associated with a paleosol dated at 10,710 ^{14}C yrs BP in interior Alaska and comparisons with spruce records in northwestern North America. Unrealistic migration rates from southern localities and north to south migration trends of spruce pollen and macrofossils support a spruce refugium in eastern Beringia. Spruce expanded from northern refugium around 11,000 ^{14}C yrs BP, while spruce from Alberta migrated northward around ca. 11,000 – 10,500 ^{14}C yrs BP. The Porcupine and Yukon Rivers are key migration corridors in accounting for the early presence of spruce at the Purgatory site. Since plant macrofossils help detect local populations of spruce with greater confidence than lake pollen, future studies investigating the refugium hypothesis should incorporate plant macrofossil analyses. If a refugium did exist in the northern Yukon, more multi-proxy records are needed along the Porcupine and Yukon River valley.

Table 3.1: Paleosol descriptions from Purgatory and Stevens sites

Soil	Horizon	Depth (cm)	Description
Purgatory: Soil 1 (10,710 ¹⁴ C yrs BP)	Ahkyb 1	0-7	Dark greenish gray (Gley 3/10 Y m); silty clay, clay-rich organics; cryoturbated; Ahkyb divided into two separate layers.
	Bmgjy	7-27	Very dark grayish brown (2.5 Y 3/2 m); sandy silt, with organic clay, vertical roots, discontinuous; cryoturbated, wavy Ahyb from above.
	Ahkyb 2	27-32	Dark greenish gray (Gley 3/10 Y m); organic clay, wavy boundary with sandy silt matrix, cryoturbated.
	Ck	32-42	Grayish brown (2.5 Y 5/2 m); sandy silt, shrubby roots; weak stratification of sandy silt/organics; cryoturbated, mixing of Ahyb 2 from above; effervescent.
Stevens: Soil 2 (ca. 9,700 ¹⁴ C yrs BP)	Ahyb 1	0-2	Very dark brown (10 YR 2/2 m); First thin organic layer; wood in growth position (1.5 cm diameter, 7 cm long), wood fragments/rootlets <i>in situ</i> ; epigenetic frost cracks, cryoturbated.
	Bmjy	2-23	Very dark gray (10 YR 3/1 m); mixture of sandy silt with fine textured organics; massive; frost cracks.
	Ck	23-33	Olive gray (5 Y 4/3 m); crudely horizontal stratified silt-clay material; discontinuous, mixed with above Ahyb.
	Ahyb 2	33-33.5	Very dark brown (10 YR 2/2 m); thin cryoturbated organic layer, splits in two, mixed with sandy silt.
	Bmjy	33.5- 36.5	Very dark gray (10 YR 3/1 m); horizontal stratified clay material

	Ck	36.5-45.5	Olive gray (5 Y 4/3 m); crudely horizontal stratified silt-clay material; discontinuous, mixed with above Ahyb.
	Ahyb 3	45.5-46	Very dark brown (10 YR 2/2 m); thin organic, wood/rootlets throughout, wavy boundary, cryoturbated.
	Bmgj	46-49	Dark brown (10 YR 3/3 m); horizontal stratified clay material, mottling, cast wedge (3-6 cm wide, 26 cm long), small rootlets.
	Ck	49-60	Olive gray (5 Y 4/3 m); crudely horizontal stratified silt-clay material; discontinuous; moderately effervescent.
Soil 3	Ahyb	0-3	Very dark gray (10 YR 3/1 m); Two very thin organic layers (< 3 mm thick); separation varies from 2-4 cm, cast wedge (2-3 cm long), syngenetic frost cracks, rootlets/macro wood abundant; cryoturbated, cruder on lower layer.
	Ck	3-28	Olive brown (2.5 Y 4/3 m) and light yellowish brown (2.5 Y 6/3 m); silt clay, massive, discontinuous; rootlets small; syngenetic frost cracks form vertically; moderate effervescence.
Soil 4	Ahyb	0-5	Very dark gray (7.5 YR 3/1 m); variable thickness of organic layer (0-5 cm), wavy layers, woody surface; frost cracks and cast wedges extend 3cm down, 2cm wide; extensive rootlets; cryoturbated; weak effervescence.
	Ck	5-25	Light brownish gray (10 YR 6/2 m) with discontinuous bands of olive (5 Y 5/3 m); rich clay with sandy silt; massive, wavy boundary; discontinuous Ahyb occurs within horizon (to 25 cm); sandy silt strongly effervescent, otherwise weak effervescence.
Soil 5 (ca. 8,300 ¹⁴ C yrs BP)	Ahb	0-2	Very dark gray (10 YR 3/1 m); fibrous organic layer, linear, continuous boundary; rootlets and wood on surface, roots vertical for 10 cm; weak effervescence.
	Bmj	2-7	Grayish brown (2.5 Y 5/2 m); rich clay, linear, sharp boundary with Ck below, massive; some rootlets; weak effervescence

Soil 6 (ca. 9,200 ¹⁴ C yrs BP)	Ck	7-25	Grayish brown (2.5 Y 5/2 m); sandy silt; strong effervescence.
	Ahyb	0-3	Very dark gray (10 YR 3/1 m); thin organic layer (< 2 mm), splits in two, wavy boundary; wood/rootlets on top; strong effervescence.
	Bmgjy	3-20	Dark grayish brown (2.5 Y 4/2 m); clay silt, massive, mottling; rootlets; mixed with Ck; strong effervescence.
Soil 7 (ca. 6,950 ¹⁴ C yrs BP)	Ck	20-27	Dark olive gray (5 Y 3/2 m); clay, massive, discontinuous, smooth; some wood; strong effervescence.
	Ahb	0-6	Very dark gray (7.5 YR 3/1 m); woody organic layer, varies 3-6 cm, continuous, linear, sharp contact, tree stumps; no effervescence.
	Bmkgj	6-17	Very dark brown (7.5 YR 2.5/2 m); silt, massive layer from 5-10 cm, abrupt; weak effervescence.
Soil 8 (ca. 6,950 ¹⁴ C yrs BP)	Ck	17-23	Grayish brown (2.5 Y 5/2 m); silty clay, massive, discontinuous, smooth; weak effervescence, silt sand below has strong effervescence.
	Ahb	0-7	Dark reddish brown (2.5 YR 3/4 m); wood rich organic layer ranging from 3-7cm, wavy boundary, vertical rootlets, tree stumps; no effervescence.
	Byk	7-40	Light olive brown (2.5 Y 5/6 m); silt, massive, smooth, inclusion of Ahb, wavy boundary; frost cracks; weak effervescence.
	Ck	40-45	Grayish brown (2.5 Y 5/2 m); clay, discontinuous, sharp boundary with sandy silt below; frost cracks; some rootlets; weak effervescence.

N.B. Radiocarbon ages of soils are listed in Table 3.4. Descriptions follow the Canadian System of Soil Classification (Soil Classification Working Group, 1998).

<i>Cicuta</i>	2					stream banks
<i>maculata/bulbifera</i>	163					Meadows, riverbanks, lakeshores
<i>Mentha cf. arvensis</i>		1				Shallow ponds, lakes
<i>Hippuris vulgaris</i>			11			Moist saline areas, clearings
<i>Chenopodium</i> sp.	1%				1	Edge of shallow ponds, meadows, lakeshores, banks
<i>Potamogeton</i> sp.						Various
<i>Geum</i> sp.						Various
<i>Potentilla</i> sp.						Various
Polygonaceae undiff.			3			Various
<i>Ranunculus</i> undiff.				1	1	Various
<i>Typha latifolia</i>						Calcareous shallow ponds
cf. <i>Anemone</i> sp.	2	2				Wet moist places
Fabaceae undiff.	1		3		1	Various

Notes: Nomenclature from Montgomery (1977). Habitat descriptions adapted from Cody (1996).

Table 3.3: Chart showing abundance of macroremains recovered from the Purgatory site

Sample & Fraction	Large wood	Small wood	Stem	Bark	"Seeds"	Insect parts	Roots/organics
G2 > 2 mm	1	2	X	1	X	X	X
> 1.18 mm	1	1	1	1	X	X	X
G5 > 2 mm	1	3	X	1	X	X	X
> 1.18 mm	2	2	X	1	X	X	X
G8 > 2 mm	2	1	1	1	X	X	X
> 1.18 mm	2	3	X	1	X	1	1
G10 > 2 mm	4	X	1	3	X	X	X
> 1.18 mm	2	1	1	2	X	X	X
G13 > 2 mm	1	X	1	X	X	X	X
> 1.18 mm	X	X	1	1	X	X	X
G17 > 2 mm	1	X	X	X	X	X	X
> 1.18 mm	1	X	X	1	X	X	X
G21 > 2 mm	1	X	1	X	X	X	X
> 1.18 mm	1	1	1	1	X	1	X
G24 > 2 mm	1	X	1	X	X	X	X
> 1.18 mm	1	X	1	X	X	X	X
G27 > 2 mm	X	X	1	X	X	X	X
> 1.18 mm	X	X	1	X	X	X	X
G30 > 2 mm	X	X	X	X	X	X	X
> 1.18 mm	X	X	1	X	X	X	X

Note: X = absent, 1 = rare, 2 = present, 3 = common, 4 = frequent and 5 = abundant. Numerical rating based on coverage of macroremains on Petri dish.

Table 3.4: Radiocarbon ages from Purgatory and Stevens sites

Age ¹⁴ C years BP	Lab no.	Calibrated age (yrs BP)	Material	Context	Reference
6,950 ± 80	GSC-6735	7,950 (7,800) 7,650	ca. <i>Picea</i> wood	Soil 8	Froese (unpubl)
6,990 ± 80	GSC-6690	7,960 (7,815) 7,670	<i>Picea</i> wood	Soil 8	Froese (unpubl)
6,800 ± 70	GSC-6734	7,800 (7,655) 7,510	<i>Picea</i> wood	Soil 7	Froese (unpubl)
6,950 ± 70	GSC-6731	7,940 (7,800) 7,660	<i>Picea</i> wood	Soil 7	Froese (unpubl)
7,110 ± 100	GSC-6665	8,170 (7,945) 7,720	<i>Picea</i> wood	Soil 7	Froese (unpubl)
7,390 ± 60	WAT4162	8,350 (8,195) 8,040	Tree stump	Soil 7	Froese, 2001
9,210 ± 25	UCIAMS 26759	10,490 (10,375) 10,260	<i>Rubus</i> sp. nutlets	Soil 6	This paper
8,320 ± 200	AA52065	9,750 (9,150) 8,550	<i>In situ</i> wood	Soil 5	Froese (unpubl)
9,450 ± 120	GSC-6718	11,200 (10,800) 10,400	<i>In situ</i> wood	Soil 2	Froese (unpubl)
9,660 ± 110	GSC-6707	11,250 (10,950) 10,650	<i>In situ</i> wood	Soil 2	Froese (unpubl)
9,752 ± 85	AA52066	11,350 (11,050) 10,750	Rooted stump	Soil 2	Froese (unpubl)
9,813 ± 91	AA52061	11,650 (11,225) 10,800	Detrital wood	Gleyed horizon	Froese (unpubl)
9,830 ± 130	AA52060	11,800 (11,275) 10,750	Detrital wood	Gleyed horizon	Froese (unpubl)
18,700 ± 440	AA52063	23,550 (22,250) 20,950	<i>Picea</i> needles	Detrital layer	Froese (unpubl)
42,100 ± 2,000	AA52062	48,450 (43,450) 38,450	Detrital wood	Detrital layer	Froese (unpubl)
10,270 ± 25	UCIAMS 28210	12,150 (11,995) 11,840	<i>In situ</i> wood	Sand sheet	This paper
10,710 ± 60	Beta 214273	12,860 (12,755) 12,650	<i>In situ</i> wood	Soil 1	This paper
11,420 ± 60	Beta 214272	13,410 (13,290) 13,170	<i>In situ</i> wood	Sand sheet	This paper
11,500 ± 100	WAT 4160	13,610 (13,390) 13,170	<i>In situ</i> wood	Sand sheet	Froese et al. (2005)
11,550 ± 70	WAT 4100	13,590 (13,420) 13,250	<i>In situ</i> wood	Sand sheet	Clement (1999)

Notes: Radiocarbon ages presented in stratigraphic order from youngest to oldest. Calibrated ages were calculated based on Oxcal v 3.10 (Bronk Ramsey, 2005) at 2σ. Mean calibrated age (in brackets). All ages are conventional, except UCIAMS 28210 and AA dates, which is an AMS date from wood. These ages provide chronology for the late Pleistocene based on terrestrial macrofossils.

Table 3.5: Chart showing abundance of macroremains recovered from the Stevens site

Sample & Fraction	Large wood	Small wood	Stem	Bark	"Seeds"	Insect parts
H11 > 2 mm	X	X	1	X	X	X
> 1.18 mm	1	X	1	X	X	X
H26 > 2 mm	1	X	1	X	X	X
> 1.18 mm	1	X	X	1	X	X
H43 > 2 mm	1	X	1	2	X	X
> 1.18 mm	2	1	2	3	X	X
H52 > 2 mm	X	X	X	X	X	X
> 1.18 mm	2	1	2	2	1	X
H57 > 2 mm	1	1	1	1	X	X
> 1.18 mm	1	1	1	1	X	X
H67 > 2 mm	2	1	2	2	X	X
> 1.18 mm	1	2	1	2	X	X
H100 > 2 mm	3	1	X	3	X	X
> 1.18 mm	4	1	1	5	1	X
H105 > 2 mm	X	X	X	X	X	X
> 1.18 mm	1	X	1	X	1	X
H173 > 2 mm	X	1	1	2	X	X
> 1.18 mm	2	2	X	2	1	X
H172 > 2 mm	1	X	1	1	X	X
> 1.18 mm	2	1	1	1	X	1
H166 > 2 mm	3	3	3	3	X	X
> 1.18 mm	2	1	2	2	1	1
H162 > 2 mm	1	1	1	1	X	X
> 1.18 mm	1	1	1	1	1	1
H158 > 2 mm	2	1	2	3	X	X
> 1.18 mm	4	1	3	5	1	X
H157 > 2 mm	5	1	3	3	1	X
> 1.18 mm	4	1	2	4	1	X

Note: X = absent, 1 = rare, 2 = present, 3 = common, 4 = frequent and 5 = abundant. Numerical rating based on coverage of macroremains on Petri dish. Rare to present amounts of bud covers found in H67, H100 and H173. Common amount of dung pellets in H166. Rare to present amount of moss fragments in H157.

Table 3.6: Late Pleistocene – early Holocene spruce plant macrofossil and pollen records from northwest North America and Alberta

Map number	Location	Lab no.	Age (¹⁴ C Yrs BP)	Calibrated age (Yrs BP) ^c	<i>Picea</i> with dated material	Reference	Rating ^d
1	Stevens Village, AK (65°59'N, 148°57'W)	AA52063	18,700 ± 440	23,550 (22,250) 20,950	<i>Picea</i> needles in detrital layer	Froese (unpubl)	4 ^b
2	Upper Porcupine River, Bell Basin, YK (66°51'N, 137°43.5'W)	GSC-2431	15,900 ± 160	19,450 (19,150) 18,850	<i>Picea</i> needles in detrital organic material	Hopkins et al. (1981)	4 ^b
3	Upper Porcupine River, Bell Basin, YK (66°51'N, 137°43.5'W)	GSC-2553	13,500 ± 310	16,950 (16,050) 15,150	<i>Picea</i> needles from organic pod	Hopkins et al. (1981)	4 ^b
4	Trois Cent Trente, Porcupine River, YK (67°25'N, 140°47'W)	TO-6430 & TO-6429	11,640 ± 150 – 10,530 ± 180	13,800 (12,775) 11,750	<i>Picea</i> pollen rise associated with wood fragments	Lauriol et al. (2002)	3
5	Twin Lakes, near Inuvik, N.W.T. (68°22'N, 133°44.5'W)	GSC-1514	11,500 ± 160	13,750 (13,400) 13,050	<i>Picea</i> macrofossils (Cones, cone scales, seeds) from bulk	Fyles et al. (1972)	4
6	Tuktoyaktuk Peninsula, N.W.T. (69°03'N, 133°27'W)	GSC-1237	11,500 ± 220	13,800 (13,375) 12,950	<i>Picea</i> pollen rise in bulk lacustrine sediment	Richie and Hare (1971) Lichtner	5
7	Lofly Lake, AB (54°44'N, 112°29'W)	GSC-1049	11,400 ± 190	13,700 (13,300) 12,900	<i>Picea</i> pollen rise in bulk lacustrine sediment	Federovich (1970)	5
8	Spring Lake, AB (55°50'N, 119°60'W)	-	11,000 ^a	12,960 (12,920) 12,880	<i>Picea</i> pollen rise in bulk lacustrine sediment	White and Mathewes (1986)	5
9	Eaglenest Lake, AB (57°46'N, 112°06'W)	-	11,000 ^a	12,960 (12,920) 12,880	<i>Picea</i> pollen rise in bulk lacustrine sediment	Vance (1986)	5
10	Birch Lake, AK (64°19'N, 146°40'W)	-	10,900 ^a	12,900 (12,870) 12,840	<i>Picea</i> pollen rise in bulk lacustrine sediment	Ager (1975)	5
11	Purgatory site, Yukon Flats, AK (66°14'N, 148°16'W)	Beta 214273	10,710 ± 60	12,860 (12,755) 12,650	<i>Picea</i> macrofossils and pollen associated with wood from peat	This paper	2
12	Mariana Lake, AB (55°57'N, 112°01'W)	-	10,500 ^a	12,650 (12,520) 12,390	<i>Picea</i> pollen rise in bulk lacustrine sediment	Hutton et al. (1994)	5
13	Hanging Lake, YK (68°23'N, 138°23'W)	GSC-2749	10,200 ± 190	12,650 (11,950) 11,250	<i>Picea</i> pollen rise in bulk lacustrine sediments	Cwynar (1982)	5

14	Sleet Lake, N.W.T. (69°30'N, 133°60'W)	-	10,000 ^a	11,610 (11,470) 11,330	<i>Picea</i> pollen rise in bulk lacustrine sediments	Spear (1993)	5
15	Whitefish Lake, YK (67°08'N, 137°25'W)	GSC-1829	9,530 ± 170	11,250 (10,775) 10,300	<i>Picea</i> needles associated with <i>Salix</i> wood	Lowdon et al. (1977)	4
16	Birch Lake, AK (64°19'N, 146°40'W)	-	9,500 ^a	11,000 (10,850) 10,700	<i>Picea</i> pollen rise in bulk lacustrine sediment	Ager (1975)	5
17	Wien Lake, AK (64°20'N, 152°16'W)	-	9,500 ^a	11,000 (10,850) 10,700	<i>Picea</i> pollen rise in lacustrine bulk sediments and one AMS date	Hu et al. (1993)	4
18	Antifreeze Pond, AK (62°21'N, 140°50'W)	-	9,500 ^a	11,000 (10,850) 10,700	<i>Picea</i> pollen rise in bulk lacustrine sediment	Rampton (1971)	5
19	Canyon Creek, AK (64°17'N, 146°29'W)	I-8291	9,460 ± 155	11,200 (10,725) 10,250	<i>Picea</i> cone found in paleosol	Weber et al. (1981)	1
20	Grayday Pond, YK (64°57'N, 138°15'W)	-	9,400 ^a	10,680 (10,630) 10,580	<i>Picea</i> needles found in bulk dated chronology	Cwynar and Spear (1991)	4
21	Lac Meleze, N.W.T. (65°13'N, 126°07'W)	-	9,300 ^a	10,570 (10,500) 10,430	<i>Picea</i> pollen rise in bulk lacustrine sediments	MacDonald (1987)	5
22	Tangle Lakes, AK (63°02'N, 146°04'W)	UCLA- 1858	9,100 ± 80	10,550 (10,250) 9,950	<i>Picea glauca</i> cones with <i>Populus</i> log	Schweger (1981)	4
23	SBA Site, Old Crow, YK (67°47'N, 139°50'W)	-	9,100 ^a	10,250 (10,240) 10,230	<i>Picea</i> pollen rise in bulk lacustrine sediments	Ovenden (1981)	5
24	CB Site, Old Crow, YK (68°06'N, 140°56'W)	-	9,000 ^a	10,220 (10,200) 10,180	<i>Picea</i> pollen rise in lacustrine bulk sediments	Ovenden (1981)	5
25	Harding Lake, AK (64°40'N, 149°00'W)	-	9,000 ^a	10,220 (10,200) 10,180	<i>Picea</i> pollen rise in lacustrine bulk sediments	Ager (1983)	5
26	Honeymoon Pond, YK (64°63'N, 138°40'W)	-	8,900 ^a	10,170 (10,040) 9,910	<i>Picea</i> needles found in bulk dated chronology	Cwynar and Spear (1991)	4
27	Tyrrell Lake, Doll Creek Area, YK (66°03'N, 135°39'W)	GSC-2549	8,860 ± 270	10,750 (10,000) 9,250	<i>Picea</i> pollen rise in lacustrine bulk sediments	Ritchie (1982)	5
28	Tinkdhuil, AK (66°58'N, 143°15'W)	-	8,700 ^a	9,690 (9,625) 9,560	<i>Picea</i> pollen rise in lacustrine bulk sediments	Anderson et al. (1988)	5
29	Dune Lake, AK (64°45'N, 149°00'W)	CAMS- 29563	8,670 ± 60	9,890 (9,710) 9,530	<i>Picea</i> pollen	Bigelow (1997)	3
30	Monkshood Pond, YK (64°57'N, 138°25'W)	-	8,500 ^a	9,530 (9,508) 9,485	<i>Picea</i> needles found in bulk dated chronology	Cwynar and Spear (1991)	4
31	Ped, AK (67°20'N, 142°07'W)	-	8,500 ^a	9,530 (9,508) 9,485	<i>Picea</i> pollen rise in lacustrine bulk sediments	Edwards and Brubaker (1986)	5

32	Sands of Time (66°03'N, 147°52'W)	-	8,500*	9,530 (9,508) 9,485	<i>Picea</i> pollen rise in lacustrine bulk sediments	Lamb and Edwards (1988)	5
33	Eildun Lake, N.W.T. (63°08'N, 122°46'W)	-	8,500*	9,530 (9,508) 9,485	<i>Picea</i> pollen rise in lacustrine bulk sediments	Slater (1980)	5
34	Lost Lake, AK (64°18'N, 146°41'W)	-	~ 8,500*	9,500	<i>Picea</i> pollen rise between AMS lacustrine material	Tinner et al (2006)	3
35	Birch Lake, AK (64°32'N, 146°83'W)	CAMS-25427	8,480 ± 60	9,550 (9,475) 9,400	<i>Picea</i> pollen	Bigelow (1997)	3
36	Jan Lake, AK (63°34'N, 143°54'W)	-	8,400*	9,470 (9,450) 9,430	<i>Picea</i> pollen rise between AMS lacustrine material	Carlson and Finney (2004)	3
37	Near Klaune Lake, YK (61°10'N, 138°38'W)	I-10524	8,390 ± 135	9,600 (9,300) 9,000	<i>Picea</i> needles peat in ice-wedge cast	Hopkins et al. (1981)	4
38	Windmill Lake, AK (63°39'N, 148°48'W)	Close to CAMS-22021	8,300*	9,410 (9,340) 9,270	<i>Picea</i> pollen rise associated closely with aquatic moss date	Bigelow and Edwards (2001)	3
39	Sulphur Lake, YK (60°95'N, 137°95'W)	BETA-109438	8,240 ± 50	9,410 (9,220) 9,030	<i>Picea</i> seed	Lacourse and Gajewski (2000)	1
40	Old Crow River, YK (68°03'N, 139°49'W)	GSC-1243	8,100 ± 160	9,450 (9,000) 8,550	<i>Picea</i> needles from bulk	Matthews (1979)	4
41	Fairbanks area, AK (64°51'N, 148°02'W)	PIC-5	8,080 ± 165	9,450 (9,000) 8,550	<i>Picea</i> needles associated with wood date	Péwé (1975), Matthews (1979)	4
42	North bank of White River, AK (61°45'N, 141°37'W)	Y-2302	8,020 ± 120	9,300 (8,925) 8,550	<i>Picea</i> wood	(Denton, 1974)	4

Notes: a) Dates based on >10% rise in *Picea* pollen, with no associated conventional or AMS date, are reported here as original author suggested

b) Caution on possibility of *Picea* macrofossils being re-deposited c) Calibrated ages were calculated based on Oxcal v 3.10 (Bronk Ramsey, 2005) at 2σ. Mean calibrated age (in brackets) ranges from 19,150 – 8,925 cal. yr BP d) Confidence Rating (1= highest confidence, 5= lowest confidence): 1) Direct AMS date from plant macrofossil, 2) Plant macrofossil associated with AMS date from macrofossil material, 3) Stomates and pollen associated with AMS date from macrofossil material, 4) Plant macrofossil associated with conventional date from bulk material and 5) Pollen associated with conventional date from bulk material.

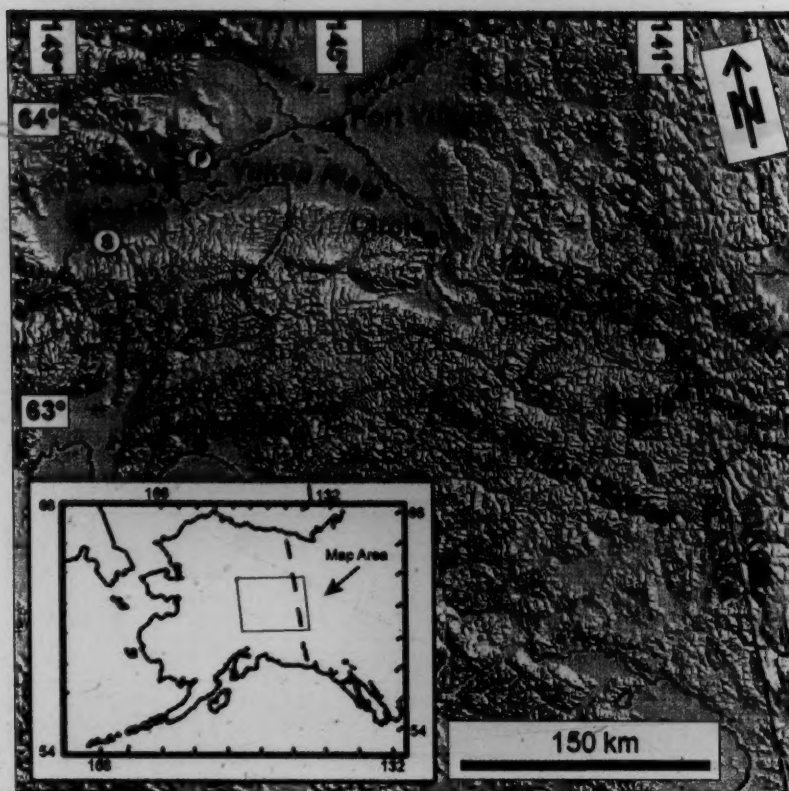


Figure 3.1: Location map of Purgatory (P on inset map) and Stevens site (S on inset map) in Yukon Flats, central Alaska.



Figure 3.2: Purgatory bluff with paleosol dated at ca. 10,700 yr BP.

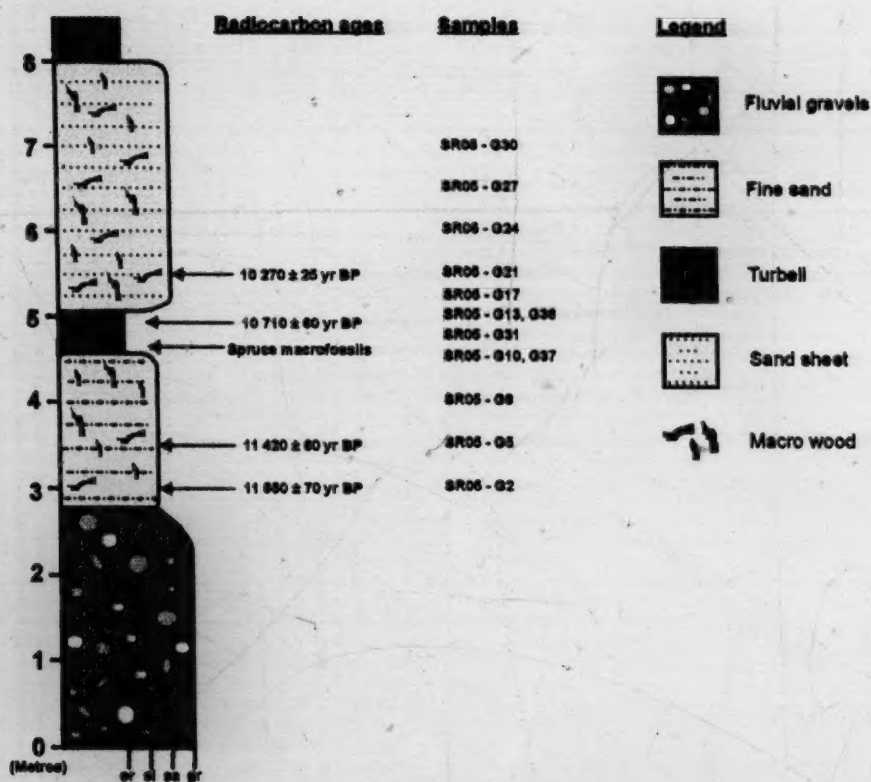


Figure 3.3: Purgatory stratigraphy with sample locations and radiocarbon ages.

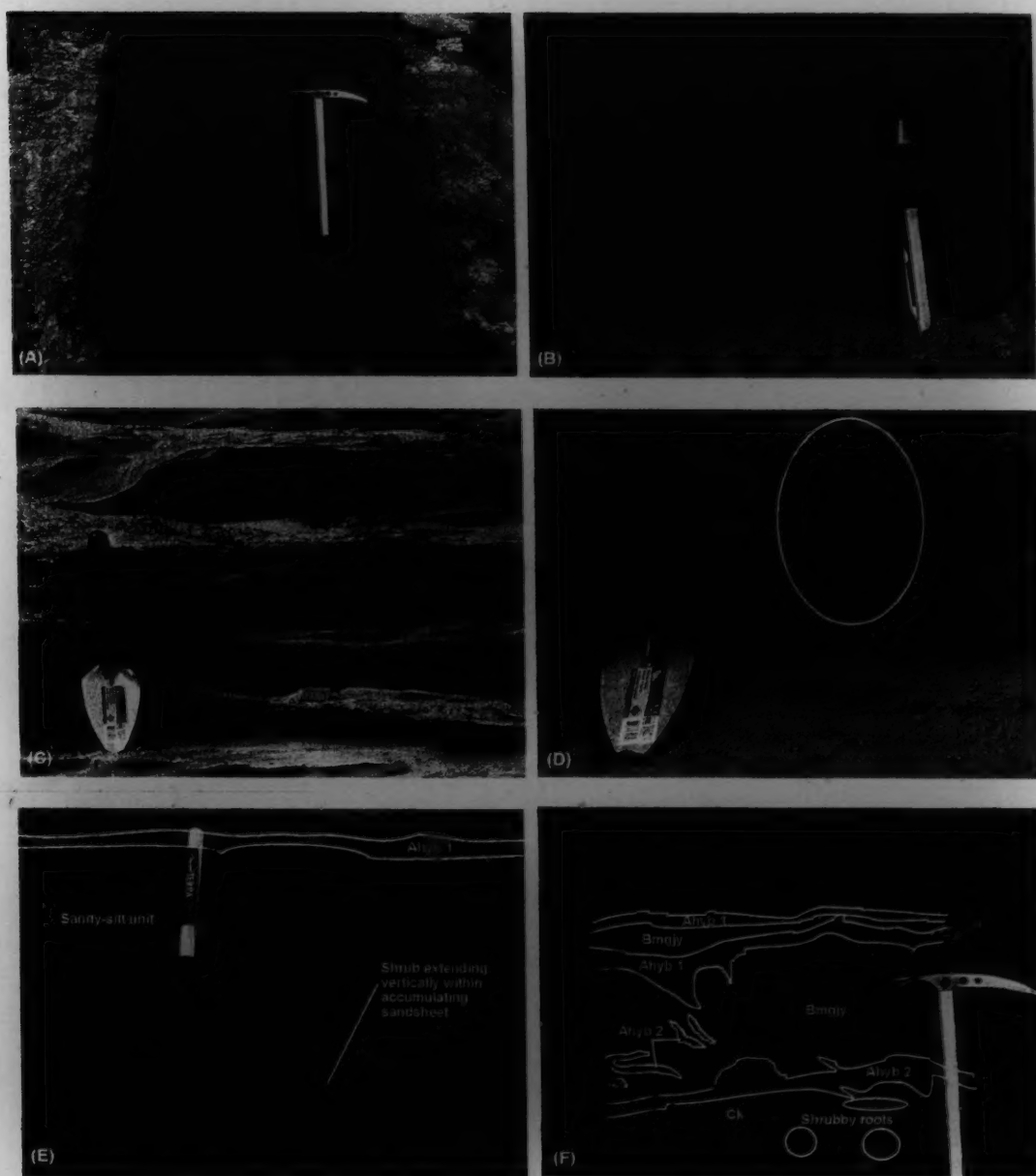


Figure 3.4: (A) Stratified eolian sand sheet underlying the paleosol (B) Cross-bedding in the first eolian sand sheet at Purgatory (C) Eolian sand in a southerly direction underlying the paleosol (D) Caribou dung within eolian sand sheet (E) Large shrub vegetation extends vertically through sand sheet unit, suggesting rapid accumulation (F) Heavily cryoturbated paleosol at Purgatory with organic layers locally dividing in to three layers.



Figure 3.5: (A) *Picea* needle from Purgatory paleosol (B) Cross-section of the Purgatory *Picea* needle (C) Purgatory *Picea* wing above modern *Picea glauca* wing (accession no: S214) (D) SEM image of modern *Picea glauca* needle tip (E) SEM image of *Picea* cf. *glauca* needle tip from soil 8 at Stevens site (F) SEM image of a cross-section of a modern *Picea glauca* needle (G) SEM image of a cross-section of a *Picea* cf. *glauca* needle from soil 8 at Stevens site.



Figure 3.6: Stevens bluff with lateral extensive paleosols (Soil 2 shown).

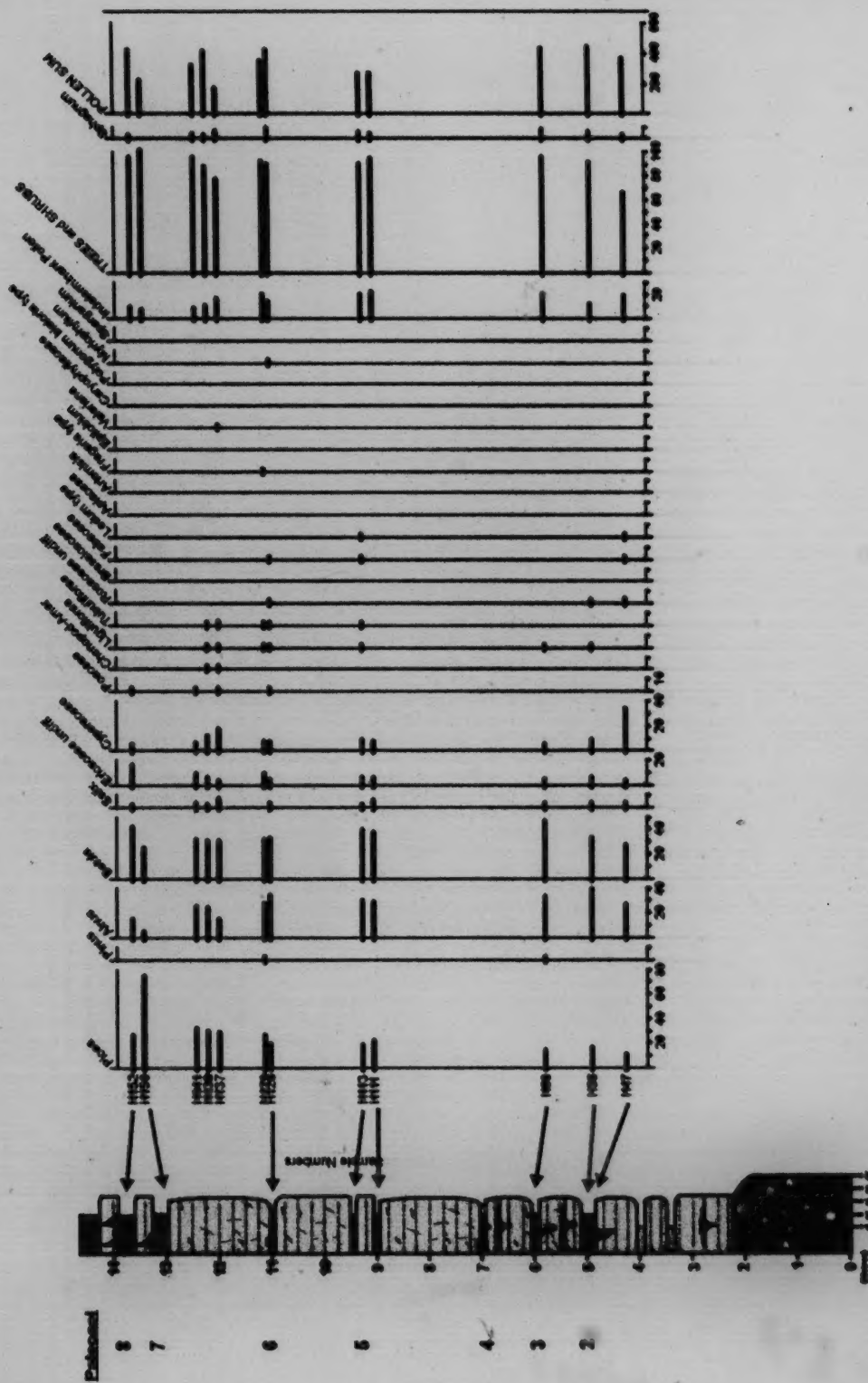


Figure 3.7: Stevens stratigraphy with soil numbers and pollen results.

Legend



Loess



Gelisols



Inceptisols



Gleyed horizon



Syngenetic
frost cracks



Wood/rootlets



In-situ
tree stumps

Figure 3.7 continued.



Figure 3.8: (A) Wedge cast in soil 2 at Stevens suggests freeze-thaw activity (B) Syngenetic frost cracks occur through most of the unit, suggesting cyclic moist-dry periods (C) Lateral beds of clay and sandy silt suggest changing levels of energy of the depositional environment. Notice *in situ* wood growing at the sides (D) Soil 2 (E) Soil 3 (F) Soil 4.

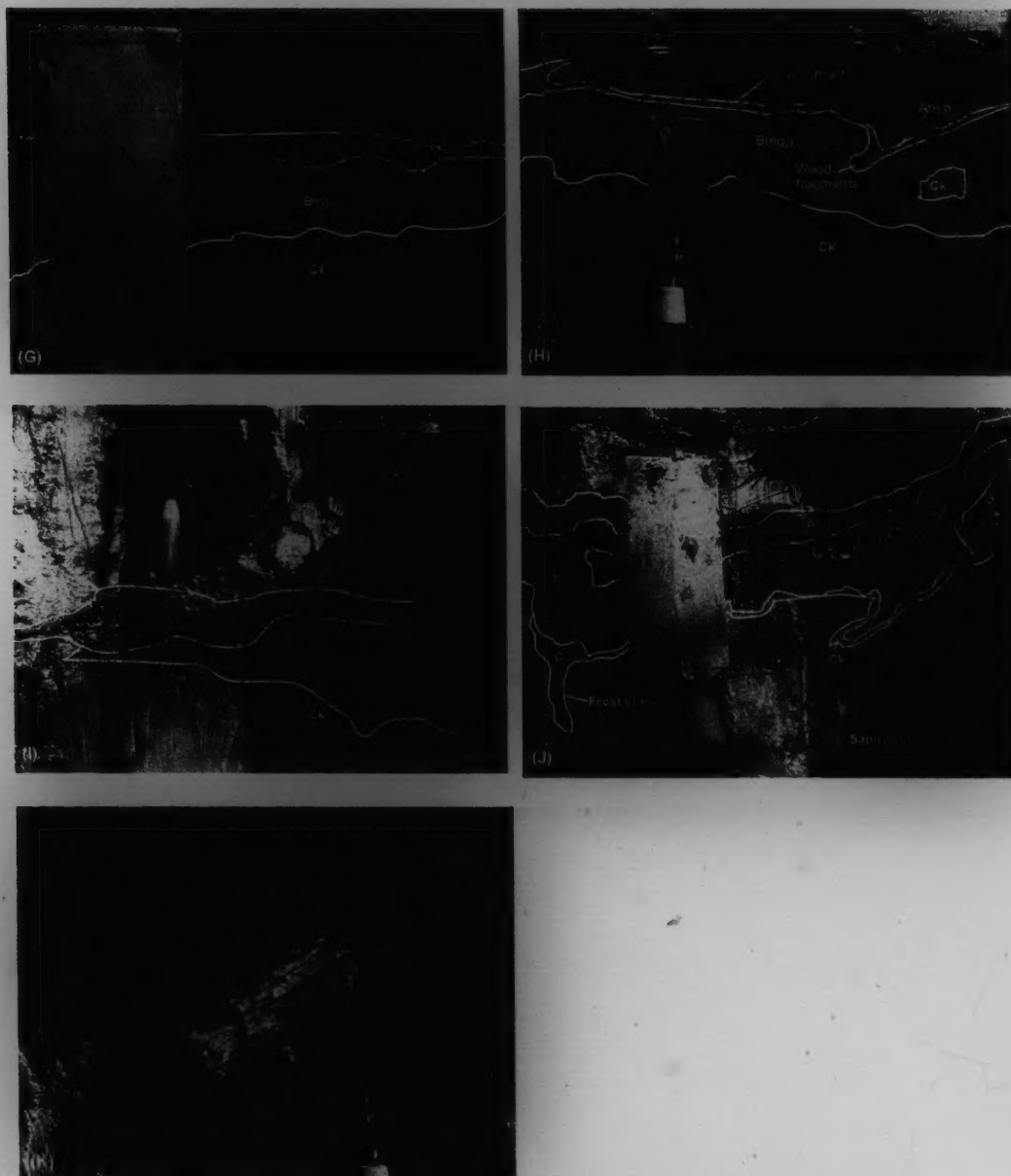


Figure 3.8 continued: (G) Soil 5 (H) Soil 6 (I) Soil 7 (J) Soil 8 (K) *In situ* spruce stump growing from soil 8 suggests rapid loess accumulation in a matter of decades.

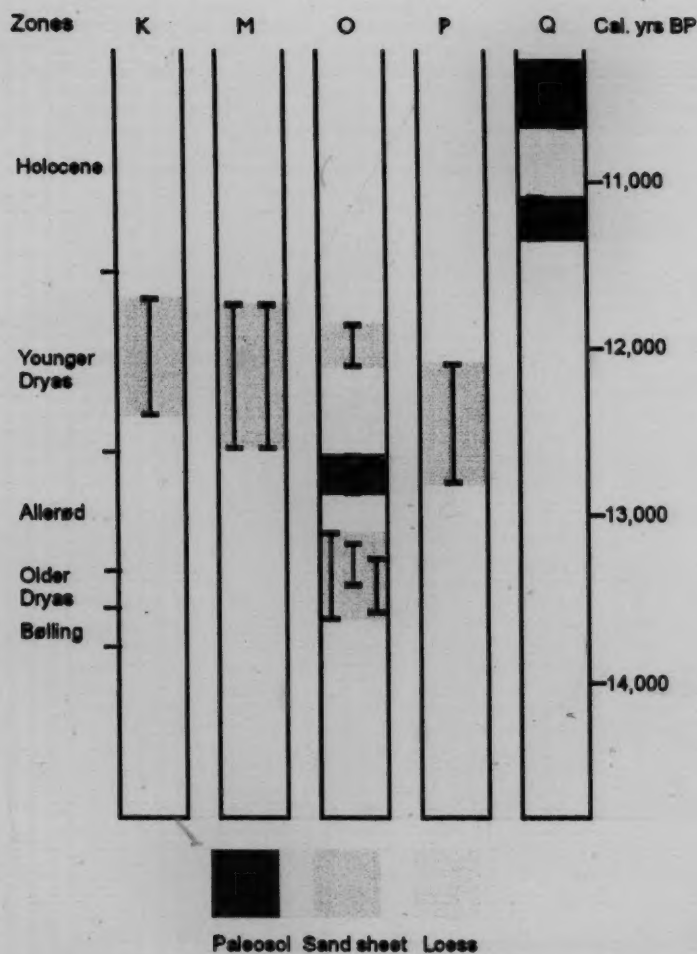


Figure 3.9: Comparison of sand sheets dated along the Yukon River, Yukon Flats, central Alaska with late Pleistocene zones from European chronology following Litt et al. (2001). All ages are from Froese et al. (2005) and presented in calibrated years B.P. (2 sigma) (Bronk Ramsey, 2005). O = Purgatory site, Q = Stevens site. All other letters correspond to sites in Froese et al. (2005).

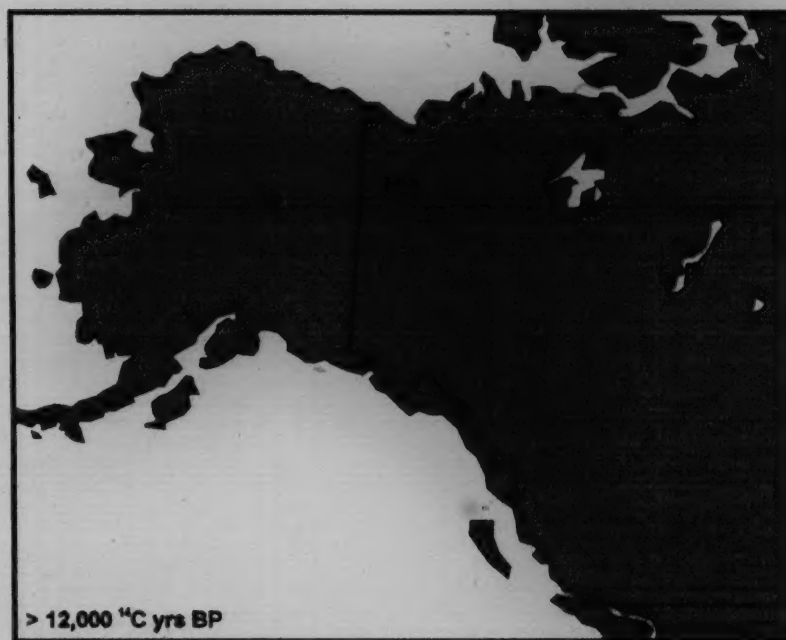
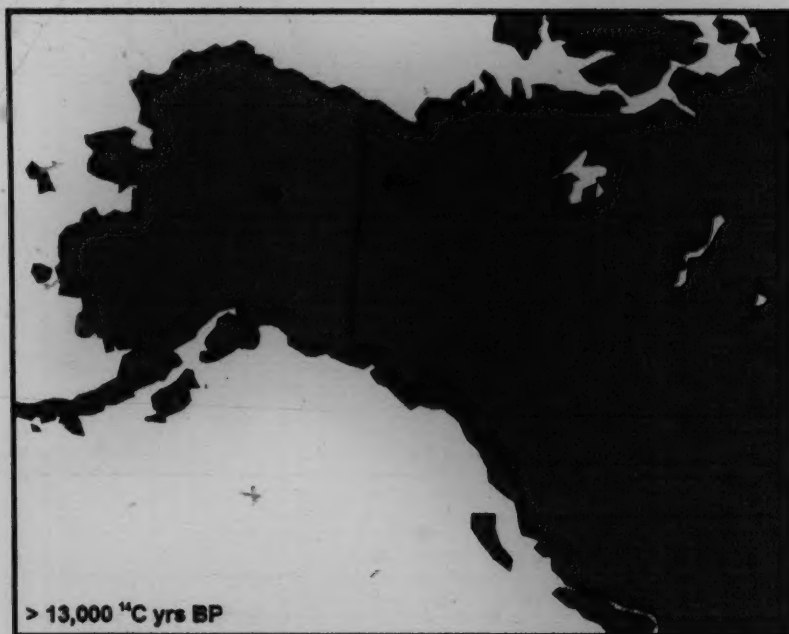


Figure 3.10: Maps of spruce pollen (>10%) and plant macrofossils in eastern Beringia between 13,000 and 8,000 ^{14}C yr BP. Green dots = confidence rating of 1 or 2, yellow dots = confidence rating of 3 and red dots = confidence rating of 4 or 5.

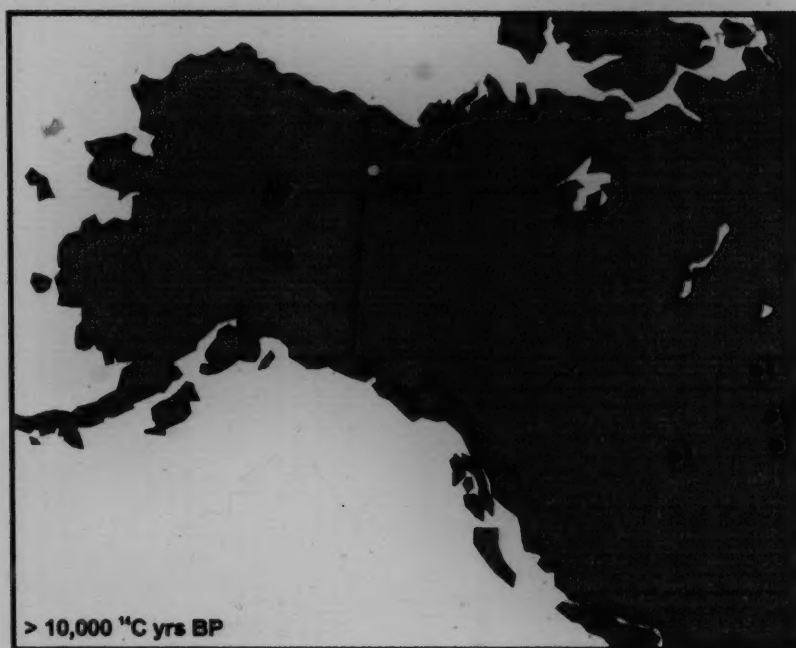
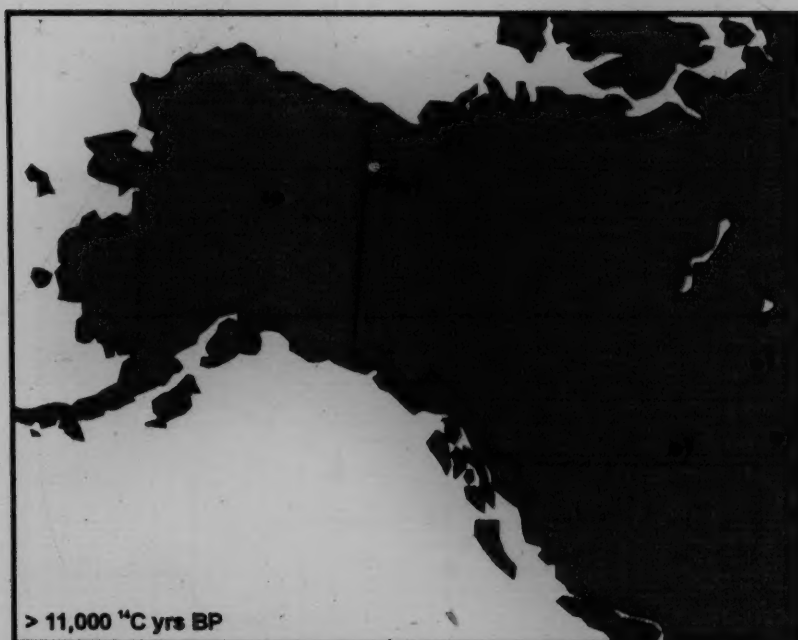


Figure 3.10 continued

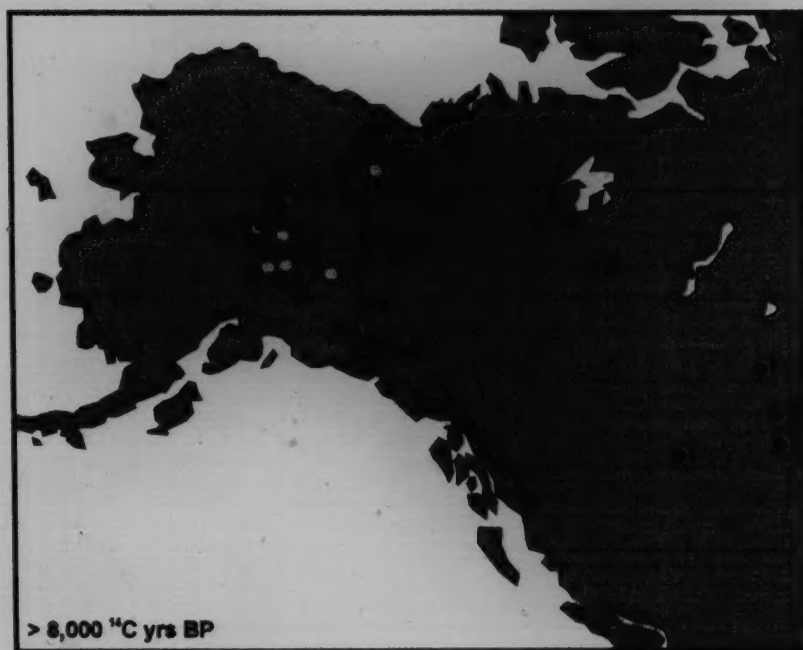


Figure 3.10 continued

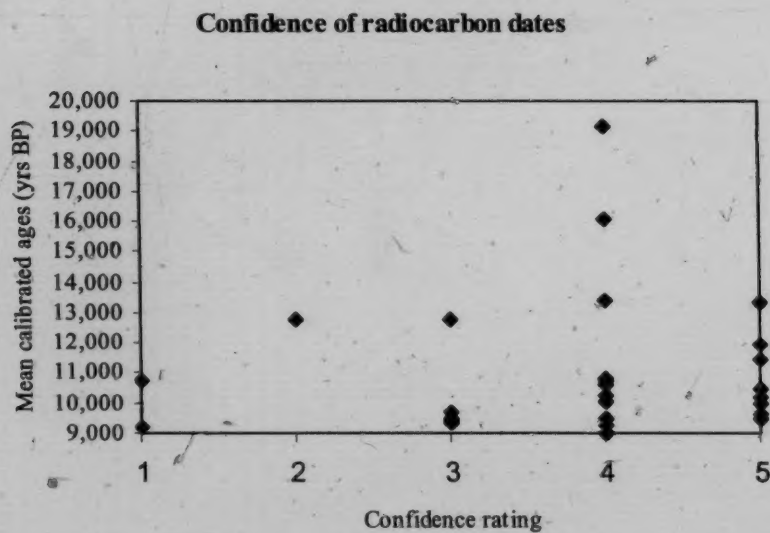


Figure 3.11: Confidence rating of dates for spruce records in eastern Beringia (1= highest confidence, 5= lowest confidence).

3.7 References

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CHAPTER 4 – CONCLUSIONS

4.1 Conclusions

This thesis presents new paleoecological data for the late-Pleistocene – early Holocene transition, from the Yukon Flats of central Alaska. The Yukon Flats contains numerous loess and sand sheet deposits which have been exposed by lateral migration of the modern Yukon River. These cut-bank exposures provide a near continuous record of the landscape during a time of abrupt climate change and changes in the flora and fauna. The loess deposits are punctuated with interbedded paleosols which contain past vegetation remains in the form of plant macrofossils and pollen, which can also be dated. The plant macrofossils and pollen from these paleosols and loess deposits provides an opportunity to record local vegetation and infer paleoenvironmental conditions during the time of deposition.

The Dalton Highway bridge site contains one of the earliest beaver dams (ca. 9,300 ^{14}C yrs BP) in Alaska, following the last glaciation. The plant macrofossil assemblage from associated deposits provides a snapshot of the early Holocene biogeography of the local area. The results suggest that during the early Holocene, the Yukon River region experienced warmer and wetter conditions compared to the previous conditions of the full-glacial. The temperatures may well have been higher than modern day values as suggested by comparing the northern limits of identified aquatic taxa, with the locality of our site. The appearance of the beaver dam itself, suggests sufficient standing water on the upland surface and the availability of local trees used to build the dam.

The Purgatory site, a terrestrial setting of late Pleistocene time, records the earliest post-glacial spruce in Alaska at ca. 10,700 ^{14}C yrs BP. The spruce macrofossils found within the paleosol and

high spruce pollen (> 26%) close to the soil suggests that spruce was present, in the local vicinity, ca. 2000 years earlier than previous records in Alaska. These spruce macrofossils and pollen at Purgatory, when compared to previous spruce records in northwestern North America, suggest that a boreal refugium may have existed during glacial times within eastern Beringia.

The Purgatory site also has implications for abrupt climate oscillations during the late Pleistocene. The paleosol containing spruce macrofossils is interbedded within two eolian sand sheets. The timing of deposition is synchronous with climate oscillations recorded in the North Atlantic borderlands. The underlying eolian sand sheet may have resulted from a cooling trend recorded in Europe known as the Older Dryas. Similarly, the overlying sand sheet, above the paleosol, is congruent with the Younger Dryas, a cold event lasting 1000 years. The paleosol in between marks an important transition in climate. The paleosol and the growth of local spruce trees and shrubs suggest conditions are stable with suitable temperatures and moisture availability. In the North Atlantic record, the Allerød event occurs during the same time. At Purgatory, it is suggested that the paleosol is linked to the Allerød event.

The Stevens site provides a continuous terrestrial record of the early Holocene. Several paleosols interbedded with loess suggests that conditions are improving though not entirely stable. High spruce pollen percentages throughout the exposure suggests that spruce was in the local vicinity from ca. 9,700 ^{14}C yrs BP to 6,900 ^{14}C yrs BP. Interestingly, spruce needles have been directly dated near the Stevens site, in the lower sediments, at $18,700 \pm 440$ ^{14}C yrs BP. This date would be direct evidence of a spruce refugium in eastern Beringia, as the regions beyond were glaciated, blocking any migration from more southerly locations. However, a woody fragment from the same detrital deposits yielded an age of $42,100 \pm 2,000$ ^{14}C yrs BP. Therefore, the much older spruce needles found at Stevens is treated with caution until future dates clarify the age of the deposits.

The change from sand sheet formation at Purgatory to loess and paleosols at Stevens suggests a significant decrease in wind intensity during the late Pleistocene – early Holocene transition. Two well-developed paleosols near the top of the exposure suggest that conditions have stabilized with the development of boreal forest.

The thesis incorporates plant macrofossils with pollen analysis and in doing so, provides a detailed record of the local vegetation and its landscape. Previous vegetation records of the region are based on pollen analysis, primarily from lacustrine deposits. The chronology of these records can be subject to old carbon contamination while the pollen is determined by fluctuating lake processes. Pollen percentages and the total pollen input can also cause interpretive problems between local and regional representation of certain species. The terrestrial record presented in this thesis provides a reliable chronology, with detailed assemblages of plant macrofossils and pollen, which detect the local vegetation. The thesis contributes new vegetation records for central Alaska, and further debates the history of spruce in the region.

4.2 Further study

The following are suggestions for future studies in the region, in light of the results presented in the thesis:

General:

- More vegetation records are needed in the Yukon Flats of central Alaska, for the late Pleistocene – early Holocene, or in full-glacial time. The comparison of our record to other future studies in the area will further enhance and improve our understanding of this initial interval.

- Locating depositional settings which will provide a "gathering" assemblage of primary or in situ plant macrofossils and pollen. Beaver dams, small ponds, forest hollows are examples of such settings
- Laterally sampling an extensive paleosol may increase the chances of finding abundant macrofossils, rather than sampling vertically in one location

Future studies and suggestions for detecting a spruce refugium in eastern Beringia:

- AMS dating other spruce macrofossils from the detrital deposits near Stevens to confirm the ca. 18,700 ^{14}C yrs BP age
- If the objective is to detect local refugia of spruce trees, future studies should incorporate plant macrofossils in the record as well as pollen. Terrestrial settings would be advantageous for this objective
- In detecting a spruce refugium, this study suggests that both the Yukon and the Porcupine Rivers are important migration routes. More records are needed along these rivers to detect the earliest appearance of spruce
- As most of the earliest post-glacial spruce pollen and macrofossils occur in the northern Yukon, it is suggested that more dated plant macrofossil data are required in the area. In particular, records from the Old Crow and Bell Basin are needed to test the ages of previous detrital material
- One growing area in the debate of the history of spruce is the use of genetics. It is suggested that such methods be incorporated in central Alaska and northern Yukon, and compared with previous genetic records
- More terrestrial records of vegetation are required in Alberta, the likely northern migration route of spruce from southern locations. Previous records are based on pollen

from lacustrine sediments. The timing of post glacial spruce in northern Alberta is important regarding migration rates required for known appearances in eastern Beringia

- More climate and landscape models are needed for eastern Beringia during the late Pleistocene – early Holocene in determining if conditions suited the migration and re-population of spruce

Abrupt climate change in eastern Beringia and Stratigraphy:

- Purgatory and other eolian deposits along the Yukon River must be AMS dated to refine the timing of deposition
- Studies which focus on the local vs. regional processes of eolian deposits